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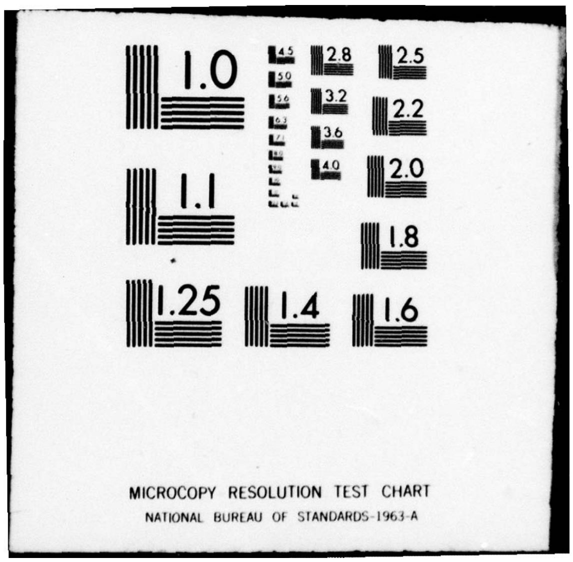
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IMPROVEMENT OF OVERLOAD CAPABILITY OF AIR CARRIER AIRCRAFT TIRES

Paul C. Durup
Lockheed California Company

October 1978

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
19 18 FAA-RD-78-133		

4. Title and Subtitle	5. Report Date
6 Improvement of Overload Capability of Air Carrier Aircraft Tires.	11 Oct[redacted]78
	6. Performing Organization Code
	8. Performing Organization Report No.
7. Author(s) 10 Paul C. Durup	12 126p.

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Lockheed-California Company Burbank, Calif. 91520	
	11. Contract or Grant No. 15 DOT-FA77WA-4069
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590	13. Type of Report and Period Covered 9 Final rept. Oct[redacted]77 - Sep[redacted]78
	14. Sponsoring Agency Code ARD520

15. Supplementary Notes

16. Abstract

This document describes the effort and findings from the work performed under Contract DOT.FA 77WA 4069. Statistical and analytical data are used to develop Transport Aircraft Ground Operations scenarios describing tire loads, deflections, temperatures, and distance traveled. These scenarios are used to aid in defining the critical conditions causing tire overload. Reasons for failure of overloaded tires are developed and used to identify potential improvements for overload capability for tires currently in use. Cost trade-off studies are made to indicate which of the improvements appear promising for further development. Concepts for new designs capable of overload are discussed along with "runflat-ideas." Using information developed in the program, tire maintenance practices that may improve the overload performance of current tires are presented.

17. Key Words	18. Distribution Statement
Aircraft Safety, Tire Failures, Overload, Runflat, Tire Safety.	Document is available to the public through National Technical Information Service, Springfield, VA. 22155.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	123	

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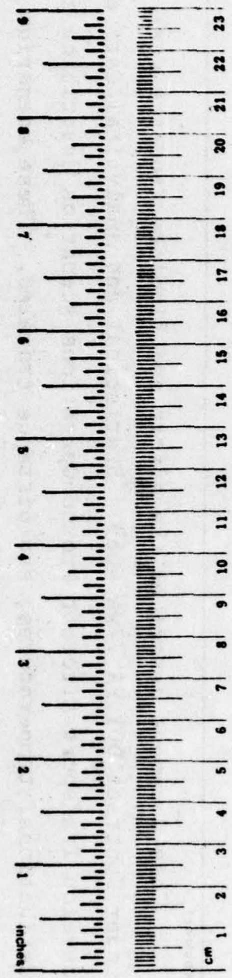
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

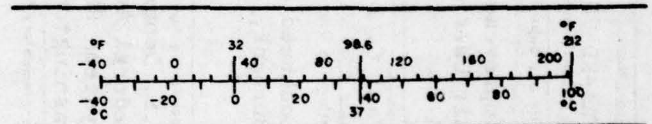
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report was prepared by the Lockheed-California Company under Contract DOT-FA77-WA-4069 and contains a description of the effort performed. This work was sponsored by the Federal Aviation Administration with R.C. McGuire as Technical Monitor. The Lockheed effort was performed under the supervision of J.E. Wignot.

The program leader was P.C. Durup of the Lockheed-California Company. Important contributions were made to the program by the Goodyear Tire and Rubber Company, which participated as subcontractor; under the direction of J.F. McNabney and H. Saviers, valuable data with regard to tire design, development and test were provided. The cooperation of R.D. Rothi and R.L. Suiter of the Douglas Aircraft Company, McDonnell Douglas Corporation, in providing measured airplane taxi tire temperature data and airplane repair cost resulting from damage occurring during tire failures is acknowledged.

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SECTION 1

INTRODUCTION

1.1 PURPOSE

A significant number of wide-body transport tire failures have been reported during the last two or three years. One of the causes of failure is "overload" which occurs when one tire on a dual or dual-tandem landing gear fails and causes one or more mating tires on the same gear to be overloaded. This study examines the operating scenarios and conditions which create an overload and adversely affect tire performance. It investigates tire design and development concepts and techniques by which air carrier tires might be improved for overload capability.

1.2 BACKGROUND

Tire failure on a dual or dual-tandem-configured landing gear places an overload on another tire on the same gear. Whether or not the overloaded tire will also fail depends on a number of factors, including the amount of the overload, the temperature of the tire when the overload occurs, the distance the tire will have to travel, and other loads applied to the tire from braking and turning. Another factor is the past service history of the tire, such as number of flights, cut repairs and the severity of the exposure to overtemperature and overdeflection. Failure of the overloaded tire at high speeds during an RTO can hamper control of the airplane, thus jeopardizing the safety of the occupants. On occasion, fires in the landing gear area have required emergency evacuation of the airplane and resulted in injury to some people involved. In addition, the cost of repairing the damage to the airplanes in some cases have exceeded one-quarter of a million dollars, not counting the airplane unavailability costs.

There are a number of factors that go into determining if a tire can perform satisfactorily when subjected to an increase in load caused by the failure of another tire on the same strut. Some are related directly to conditions existing immediately after the first tire failure. These conditions are associated with the combined vertical, side, and/or drag loads acting on the tire; the distance traveled after first tire failure, and the temperature and inflation pressure of the tire.

Other factors are related to the operational and maintenance history of the tire in question such as damage repairs made at each retread, air retention repairs, underinflation in past operations, service life (number of retreads, environment, dates on and off airplane, number of landings and installed position on the airplane), past high temperature operations, and history of mating tires (underinflated, failures, and pressure lost from activated heat plug). The influence of these factors on the capability of a tire to withstand an increase in load caused by a failure of another tire on the same strut will vary; accordingly, their significances relative to the problem have to be determined.

1.2.1 Tire Loading Effects

Structural failure of the tire results when excessive tire deflection imposes stresses beyond the rupture strength of the carcass. The service loads that produce tire deflections are vertical, lateral, and drag. Since most tire rolling is performed in essentially a straight line, the majority of deflections inflicted on the tire are symmetrical (same deflection shape on both walls of the tire) and are caused by the vertical load. Braking adds some additional symmetrical deflection to the tire depending on the amount of drag load applied. The lateral load, however, causes the tire to distort unsymmetrically, and the stresses from lateral deflection will tend to relieve the stresses caused by the vertical deflection on one side of the tire and intensify the stresses on the other side. Although the superimposed deflection produced by the drag and/or side loads may not be used as a direct measurement of the stresses imposed on the tire at a given point, the deflections do provide an indication that under conditions of combined loading the overload margin is reduced.

In the case of main-gear tires, calculations show that the amount of deflection with the same percentage of rated vertical load can vary depending on the gear configuration. In the case of dual-wheel gears in normal operations, the side load seldom exceeds 0.13 times the vertical load. On a dual-tandem gear in normal operations, the side load of the aft wheels can exceed 0.3 times the vertical load. In some ground operations, where a small radius turn is required, side loads acting on the aft tires can exceed 0.5 times the vertical load. Figure 1-1 illustrates the load distribution of a two-gear, dual-tandem configuration in a normal 65-foot radius taxiway turn in which the side load exceeds 0.25 times the vertical load on the number one rear tire (1R).

Table 1-1 presents a typical commercial transport airplane flight profile weight mix. Normal and overload tire deflections are also given in Table 1-1 for straight roll, and indicate that, except for one weight, the deflections are all below 50 percent.. It is the contention of the aircraft tire industry that as tire deflection is increased above 50 percent, tire life, as a function of roll distance, is greatly reduced.

Air carrier tire load-carrying capability has been improved in some cases by new test demands on the tires and retreads. For example, one overload test consists of rolling the tire at 1.5 times the rated load for a distance of at least 19,000 feet at a velocity of 40 knots. This loading simulates an operating condition of 45 percent tire deflection.

1.2.2 Tire Operations History

During operations, tires are removed for wear, cuts, leaks, rupture, overheat, underinflation, tread separation, out of limits, and burned. The tires are inspected, some are repaired, a large number are retreaded and placed back in service, and some are scrapped. Table 1-2 shows the reasons for tire removal during typical operations of a wide-body commercial transport. At least 79 percent of those removed were returned to service. This weeding out process results in eliminating some operationally weak tires from service. A review of the reasons for removal, however, suggests that one of the other tires on the landing gear may have been subjected to an overload for an undetermined ground-roll distance and speed. For example, from Table 1-2 it

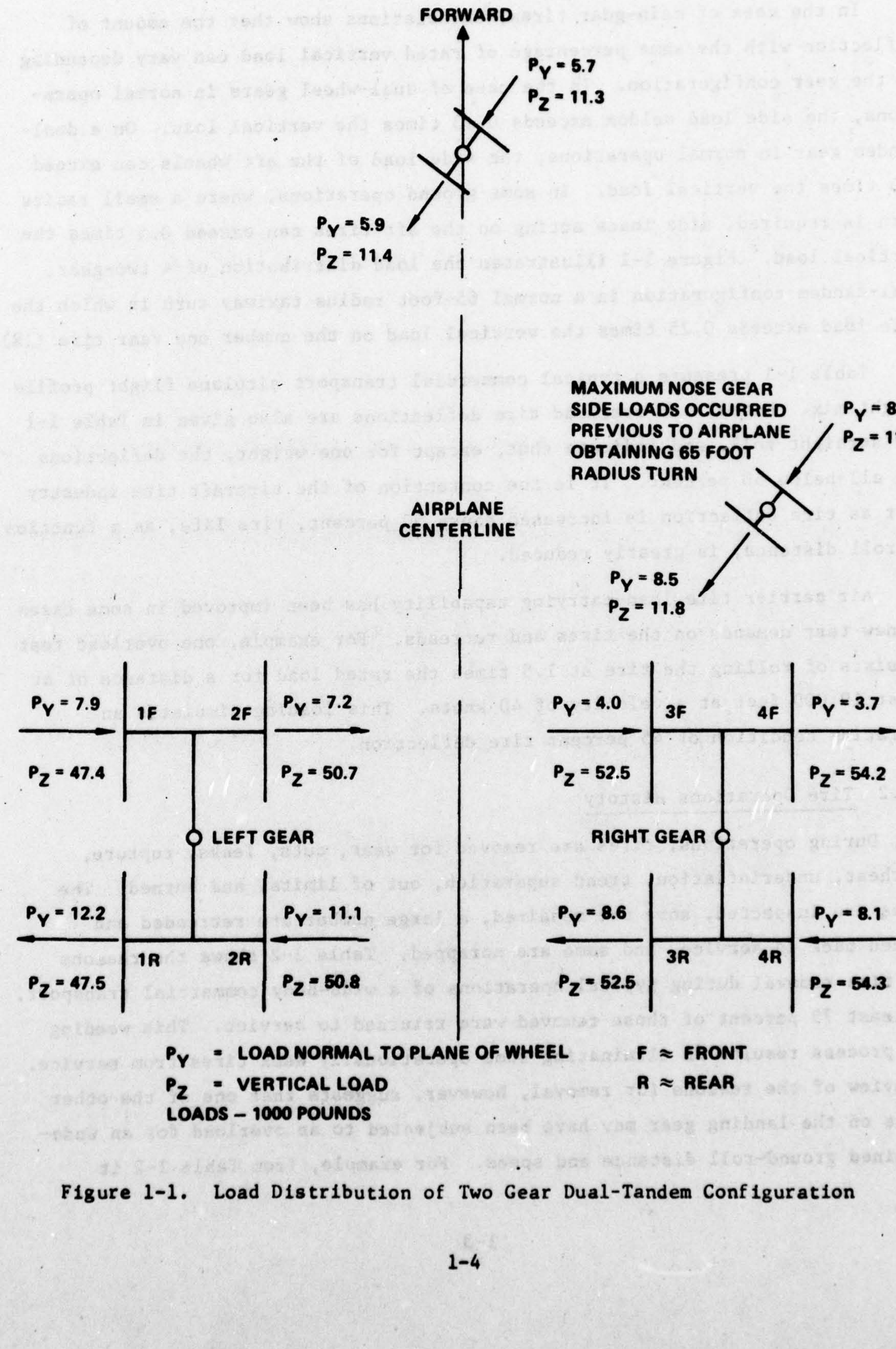


Figure 1-1. Load Distribution of Two Gear Dual-Tandem Configuration

TABLE 1-1. TYPICAL COMMERCIAL TRANSPORT AIRPLANE FLIGHT PROFILE MIX

TAKEOFF			LANDING			
NON-DIMENSIONAL WEIGHT (1)	% TIRE DEFLECTION (2)		NON-DIMENSIONAL WEIGHT (1)	% TIRE DEFLECTION (2)		PERCENT OF FLIGHTS
	NORMAL	OVERLOAD		NORMAL	OVERLOAD	
0.958	29.7	52.9	0.710	22.9	40.4	15.2
0.900	28.2	49.9	0.809	25.5	45.7	10.9
0.786	25.1	45.0	0.703	22.9	40.4	10.4
0.847	26.7	47.2	0.809	25.5	45.7	21.7
0.745	24.4	42.3	0.708	23.6	40.4	24.8
0.847	26.7	47.2	0.810	25.5	45.7	4.25 (3)
0.805	25.5	45.7	0.776	25.1	44.2	4.25 (3)
0.771	25.1	44.2	0.759	24.4	43.0	4.25 (3)
0.754	24.4	42.7	0.742	23.6	41.9	4.25 (3)

(1) Weight of Interest Divided by Design Takeoff Weight

(2) Percent Rated Load Deflection

(3) Training Flights

TABLE 1-2. TIRE REMOVAL DATA - TYPICAL FOR ONE AIRLINE

AIRPLANE LANDINGS	TIRE REMOVALS	REASONS									
		WORN	CUT	LEAK	RUPTURE	OVER HEAT	WRONG PRESS	BROKEN CARCASS	TREAD SEPARATION	BURNED	OUT OF LIMITS
49,198	2,373	1,699	458	45	15	1	8	16	60	10	61
NUMBER SCRAPPED		4 for age	391	13	15	1	7	15	36	8	UNKNOWN

appears that a number of the 68 (sum of leakers, ruptures, and wrong pressures) mating tires that were not removed may have suffered some overload damage and might not be capable of sustaining another overload condition if another mating tire failed.

If commercial transport airplane tires are to be capable of sustaining an overload condition without failure, consideration must be given to the design of the tire and to the factors that tend to degrade the tire during operations, servicing, and maintenance throughout its useful life. For example, if a tire is installed on rear positions of dual-tandem gears for most of its useful life, Figure 1-1 suggests that it will have been exposed to a much greater number of large flexures than a tire that is alternated between the front and rear after each retread. Normally, no effort is made to control the installation position; therefore, tire capability for overload could vary from tire to tire.

High temperatures previously experienced by tires can affect the overload capability of the tires. Braking, operational environment, and operations that result in self-generated heat are contributors to the adverse temperatures experienced by tires. A severe RTO usually signals the operator that the tires involved most likely have suffered damage to a degree that will require the tires to be taken out of service. The less severe RTOs and cases of heavy braking during a landing, wherein increased temperatures are encountered without obvious clues of damage, will most likely result in varying degrees of degradation of tire-overload capability with the tire remaining in service. Although FAA Advisory Circular 43.13-1A states that the airworthiness of retreaded tires shall not be adversely affected as a result of being subjected to extreme ambient temperatures encountered during normal airplane operation, some degradation in overload capability may be expected. Under conditions of higher ambient temperature, takeoff and landing speeds are higher, resulting in longer roll distances and a larger braking period during landing. Since the heat generated by brakes will not dissipate as fast in high ambient temperatures as it does in low temperatures, the amount of heat transferred to the tires will be greater. Accordingly, temperatures experienced by tires operated from airfields with higher ambient temperatures will experience much higher carcass temperatures than would normally be expected. Self-generated

heat is a function of the amount of continuous flexing (rolling) of the tire, the hysterisis characteristics of the tire material, and the rate of heat dispersal from the tire. Thus, extremely long, continuous taxi operations under high loads, with poor heat dissipation, may result in tire degradation.

During recent years, the normal cooperative industry interest in safe tire performance has increased consistent with the advancing state-of-the-art. Tire manufacturers have instigated programs with airlines which include more rigorous inspection, tire-removal requirements, and detail computerized tire records. Under these programs, tires which are removed for causes such as cuts, reduced inflation pressure, unusual heat exposure, and unusual operations such as running off and on runways and taxiways are more closely inspected by the retreader and in most cases scrapped. The tire logs indicate dates on and off airplane, manufacture and retread dates, number of landings per retread, cumulative landings, reason for removal of the tire, disposition of the tire, etc.

1.3 PROJECT SCOPE

This study includes a review of tire-failure data, tire-failure scenarios, inservice tire improvements for overload conditions, design concepts for new overload-capable tires, and operating techniques to minimize the potential for tire failure due to overload. The work was divided into tasks as follows.

In Task I, data concerning nose and main-landing-gear tire failures during normal operations were acquired and tabulated. A statistical evaluation of tire failures was made to determine critical points in operations for tire failure. A typical airport-airplane ground operation was used to determine tire loads and deflections for normal and overloaded tires. Using the results of the statistical and analytical evaluation, potentially critical tire-failure conditions were developed in scenario form. Task II included a review of reasons for tire failure involving information obtained in Task I; evaluation of potential design refinements to inservice tires to improve their overload capability; and a trade-off study of the refinements to determine their cost effectiveness. Task III evaluated new design concepts to provide overload capability in future tires. Operating techniques to minimize the potential for failure of overloaded tires following tire failure were devised and evaluated in Task IV.

SECTION 2

TIRE-FAILURE SCENARIO

2.1 GENERAL

The tire-failure overload scenario was developed from combined results of a statistical evaluation of tire-failure data, a typical airplane operations - airport layout, and analysis of tire temperatures, loads and corresponding deflections. The statistical evaluation provided an insight into the part of the taxi, takeoff, and landing operations that most likely result in tire overload conditions. Definition of the typical airport layout provided information that related taxi distance and taxi speeds with various ground maneuvers, such as turns and braking. The loads, deflections and temperatures that could be expected to be encountered by the tires during ground operations were determined analytically for the most critical tire and for the critical points in the ground operations as determined statistically. These data provided insight into needed improvements to increase the overload capability of the tires.

2.2 STATISTICAL EVALUATION OF TIRE FAILURE RECORDS

2.2.1 Method

Airline tire failure records and statistics for years 1968 through 1977 were acquired and analyzed to determine the most critical failure/operating conditions. Data concerning tire problems were extracted from a computerized flight safety bank, which is made up of information from the FAA Service Difficulty Reports, National Transportation Safety Board Reports, Flight Safety Foundation Reports, and miscellaneous airline reports. Incidents in which tire carcass failures occurred resulting in tire deflation were tabulated into two categories, single tire failures and multiple tire failures. In both categories, data were gathered, where available, concerning the following items:

- Number of main gears
- Number of tires on each gear
- Airport name
- Date
- Tires involved
- Mode of operation (taxi to takeoff, takeoff roll, rotation, RTO, climb, cruise, landing roll, taxi to ramp, and parked)
- Damage to airplane

The data concerning the mode of operation and gear configuration were used to help define the failure characteristics, while the damage data provided some insight into repair costs for the cost effectiveness study. In all, usable data were obtained for 128 single and 79 multiple tire failures, covering the years 1968 through 1977.

The statistical evaluation was performed by dividing the operations in which tire deflation occurs into the following nine identifiable stages:

- Taxi to takeoff
- Takeoff roll
- Takeoff rotation
- Rejected takeoff
- Airborne
- Landing
- Landing roll
- Taxi to ramp
- Parked

The data for each of the stages were categorized by main gear configuration, such as dual, dual-tandem (two main gears), dual-tandem (four main gears), and nose gear.

2.2.2 Results

The results of the statistical evaluation indicate that the tire failures for each stage of the operation are essentially independent of landing gear configuration. Tables 2-1 and 2-2 present the tire-failure percentages for each ground operation for single and multiple (two or more in same operation) tire failures, respectively.

TABLE 2-1. PERCENT TIRE FAILURES FOR EACH GROUND OPERATION - SINGLE TIRE FAILURE

Ground Operation Stage	Percent Tire Failures			
	Dual Main Gears	Dual-Tandem 2 Main Gears	Dual-Tandem 4 Main Gears	All Airplanes
Taxi to Takeoff	1	2	5	2
Takeoff Roll	61	64	60	63
Takeoff Rotation	8	5	-	5
Rejected Takeoff	-	-	-	-
Airborne	11	5	10	8
Landing	18	17	25	19
Landing Roll	1	2	-	1
Taxi to Ramp	-	-	-	-
Stopped After Landing	-	5	-	2

TABLE 2-2. PERCENT TIRE FAILURES FOR EACH GROUND OPERATION - MULTIPLE TIRE FAILURE

Ground Operation Stage	Percent Tire Failures			
	Dual Main Gears	Dual-Tandem 2 Main Gears	Dual-Tandem 4 Main Gears	All Airplanes
Taxi to Takeoff	4	5	8	5
Takeoff Roll	39	33	43	37
Takeoff Rotation	-	1	-	-
Rejected Takeoff	8	9	-	7
Airborne	-	6	-	3
Landing	30	24	31	28
Landing Roll	6	-	-	2
Taxi to Ramp	4	5	10	6
Stopped After:				
Takeoff	3	17	8	10
Landing	6	-	-	2

Seventy-eight percent of the single tire failures are associated with takeoff-related stages of operation as compared to 62 percent for the multiple tire failures. Of the 128 single tire failures, only 7 cases (5 percent) were nose gear tire failures, with all of the failures occurring during takeoff roll. Of the 79 multiple tire failure cases, only 3 cases (4 percent) were nose gear tire failures, 2 cases occurring on takeoff roll and 1 case occurring during landing. The landing case was an extremely hard landing in which 8 tires were blown, including both nose gear tires.

The statistical data on mating tire performance provides insight into the ability of the mating tire to carry overload. The study shows that the overloaded tires did not fail in 67 percent of the cases (189) where the tires traveled up to 7000 feet. In the cases (124) where the overloaded tires had to provide support for between 7000 and 14,000 feet of travel, 92 percent of these tires did not fail. Where the mating tires had to provide support for between 14,000 and 21,000 feet of travel (93 cases), 97 percent of these tires did not fail. One interpretation of these findings is that if the mating tire capability has not been weakened by previous damage or carcass deterioration from service (immediately obvious by failure of the overloaded tires), they will probably perform the overload function for a travel distance commensurate with a rejected takeoff or landing rollout plus the taxi distance to the terminal.

To summarize: the statistical data indicates that tire overload is most likely to occur during the takeoff roll; the failures can be partly attributed to long taxi distances at heavy gross weights; these conditions can cause high temperatures from self-generated tire heat; and tires in service today may be expected to perform well under overload conditions if the carcass has not been previously subjected to deleterious conditions, such as overdeflection and high temperatures.

2.3 CHARACTERISTICS OF TYPICAL AIRPORT - TRANSPORT OPERATIONS

In order to provide a scenario that is representative of the average ground operations experience of a transport tire, the salient airport

characteristics affecting the tire must be accounted for. This representation is partly developed by examining a number of airports for typical airport characteristics affecting the tire.

2.3.1 Approach

The following six airports were selected for a study of typical airport characteristics related to taxi distance, turn radii, and number of turns:

- San Francisco International
- John F. Kennedy International
- Dulles International
- O'Hare International
- Honolulu International
- Los Angeles International

Layouts of these airports were obtained and various taxi routes were established from different terminal areas. The foregoing airports were each examined for average taxi distance to takeoff and after landing, along with the average number of turns for a given radius.

2.3.2 Results

Table 2-3 presents the average distances traveled at each of the foregoing airports and the average distance for all airports for both taxi to takeoff and taxi after landing. The number of turns associated with each taxi operation are also given. The six turns each during taxi to takeoff and taxi after landing compares favorably with five for each period contained in Reference 1.

2.4 ANALYTICAL EVALUATION - CONDITIONS CAUSING TIRE FAILURE

The statistical evaluation provides information that indicates in which stages of ground operations that tire failures occur most frequently for both normal loading and overloading. Tire carcass deterioration that leads to tire failure can be caused by reduced strength from tire overheating (produced by self-generated heat and/or external heat sources, such as ambient air temperatures and brakes) and/or mechanical damage from overdeflection, cuts, and point

TABLE 2-3. GROUND OPERATIONS AT TYPICAL AIRPORT

AIRPORT	TAKEOFF				LANDING			
	TAXI DISTANCE FEET	TURN RADIUS - FEET 65	90	150	TAXI DISTANCE FEET	TURN RADIUS - FEET 65	90	150
San Francisco International	10,220	1	2	3	8,540	1	1	3
John F. Kennedy International	15,520	2	1	2	14,840	1	1	3
Dulles International	13,850	2	1	0	11,720	1	1	1
O'Hare International	15,920	2	1	2	11,060	2	1	2
Honolulu International	13,080	1	1	2	12,600	2	1	2
Los Angeles International	12,300	1	2	3	9,160	1	1	4
Average All Airports	13,500	2	2	2	11,300	1	1	3

impact. However, the magnitude of the tire deflections encountered and temperatures developed prior to the failures are not known. To obtain this information, analytical methods are necessary, preferably verified by test data.

2.4.1 Tire Deflection

The amount of tire deflection is a function of the loads (vertical, lateral, and drag) acting on the tire and the inflation pressure which governs the tire spring rate. The loads acting on the tires are derived from analysis methods commonly used by various commercial transport manufacturers. Accordingly, the methods for obtaining these tire loads are considered to be common industry knowledge and will not be discussed. However, the derivation of the equation which converts the loads to tire deflections is presented below.

The deflection produced by a vertical load is obtained from the particular tire load deflection curve and has the following form:

$$\delta_{Z_Z} = \delta_O + RF_Z \tag{1}$$

where,

δ_O = Deflection at no load - Inches

R = Slope of tire load deflection curve - Inches per pound

F_Z = Vertical load - Pounds

The following equation for vertical sink of the tire resulting from a lateral force is developed from equations given in Reference 2.

$$\delta_{Z_Y} = \frac{0.075\ F_Y}{(P + 0.24\ P_R)\ \left\{w - 0.7(\delta_O + RF_Z)\right\}} \tag{2}$$

where,

F_Y = Lateral load - Pounds

P = Tire inflation pressure - PSI

P_R = Tire rated pressure - PSI

w = Tire width - Inches

The following equation for vertical sink of the tire resulting from a drag force is developed from equations given in Reference 2.

$$\delta_{Z_X} = \frac{0.1667\ F_X}{(P + 4\ P_R)\ \left\{d_O{}^2(\delta_O + RF_Z)\right\}^{1/3}} \tag{3}$$

where,

F_X = Drag load - Pounds

d_O = Undeflected tire diameter - Inches

If equations (1), (2) and (3) are summed, multiplied by 100, and divided by the deflection of 100 percent, the following equation is obtained in terms of tire deflection percentages.

$$\delta_{Z_T} = \frac{1}{\delta_{100}} \left[\frac{7.5\ F_Y}{(P + 0.24\ P_R)\ \{w - 0.7\ (\delta_O + RF_Z)\}} + 100\ (\delta_O + RF_Z) + \frac{16.67\ F_X}{(P + 4\ P_R) \left\{ d_O^{\ 2} (\delta_O + RF_Z) \right\}^{1/3}} \right] \quad (4)$$

where,

δ_{100} = 100 percent tire deflection - Inches

δ_{Z_T} = Total vertical deflection due to combined vertical, side and drag loads - Percent

The appendix contains coding forms for programming the equation on a Texas Instrument SR-52 Calculator.

2.4.2 Tire Self-Generated Heat and Temperature Rise

As a given point on a tire tread comes in contact with the ground, the tire side wall deflects, resulting in relative motion of both the rubber and fabric in the bead area. This motion generates heat. The rate at which the heat is generated is a function of the tire deflection and the rotational velocity of the tire.

The following tire temperature rise equations were developed from Goodyear Tire and Rubber Company dynamometer test data shown in Figures 2-1, 2-2, and 2-3. The following terms apply for all equations:

$N_{R_{S/T}}$ = Number of tire revolutions - subscript S = straight taxi, subscript T = turns

$V_{\leq 30}$ = Velocities equal to or less than 30 mph

$V_{>30}$ = Velocities greater than 30 mph

$\delta_{ZT \leq 32}$ or $\delta_{ZT \leq 29.8}$ = Tire deflections equal to or less than 32 or 29.8 percent, respectively

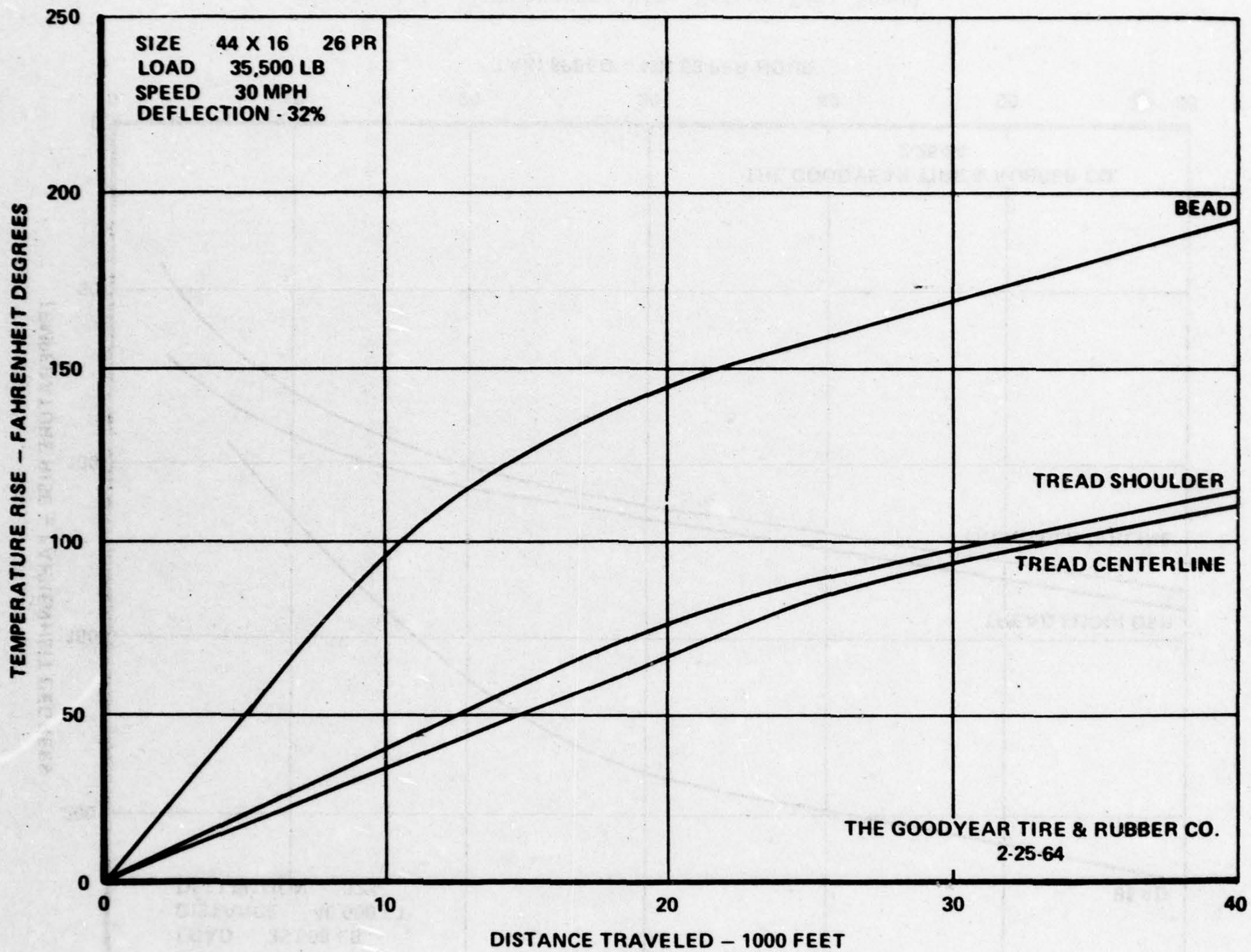


Figure 2-1. Temperature Rise Versus Taxi Distance

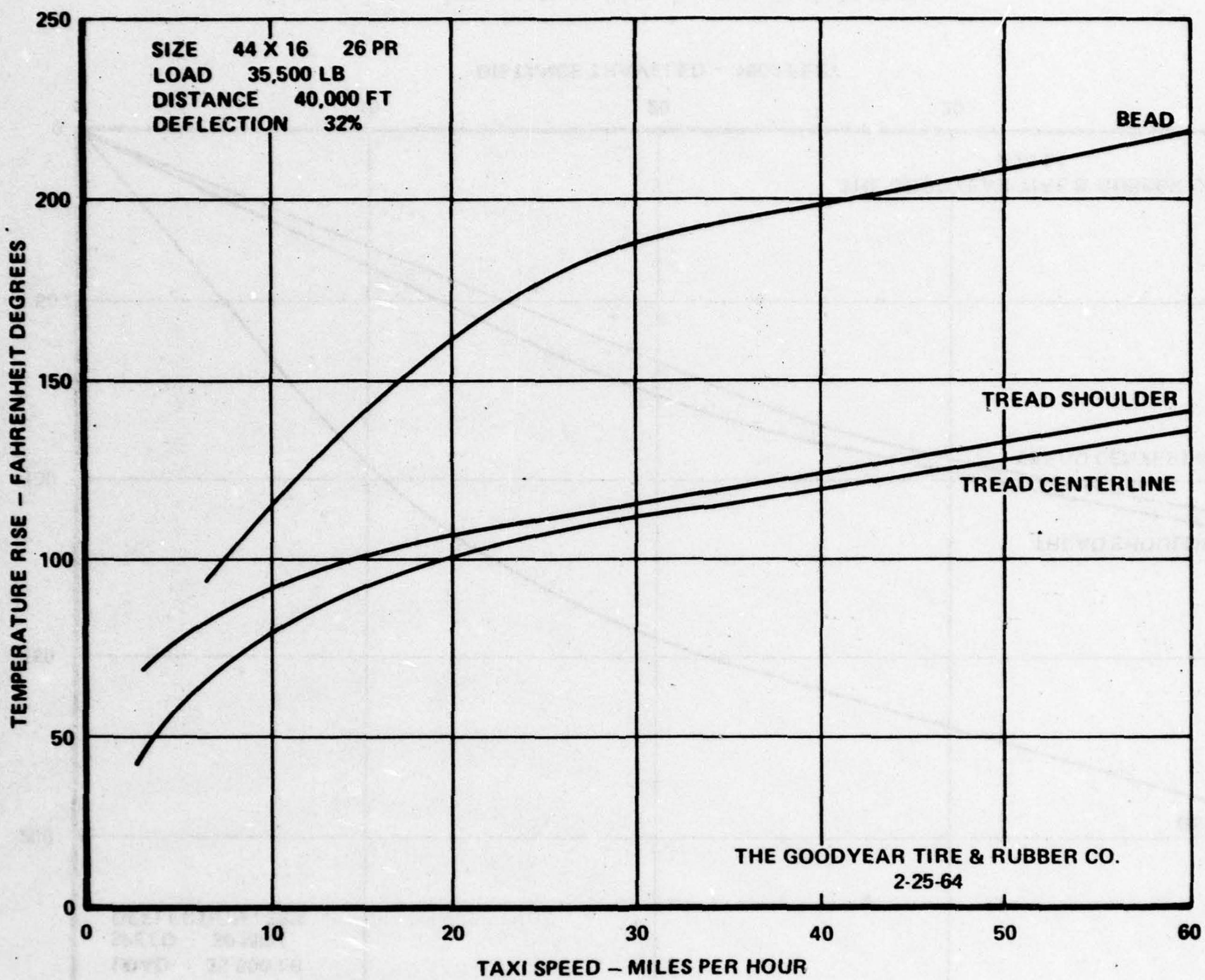


Figure 2-2. Temperature Rise Versus Taxi Speed

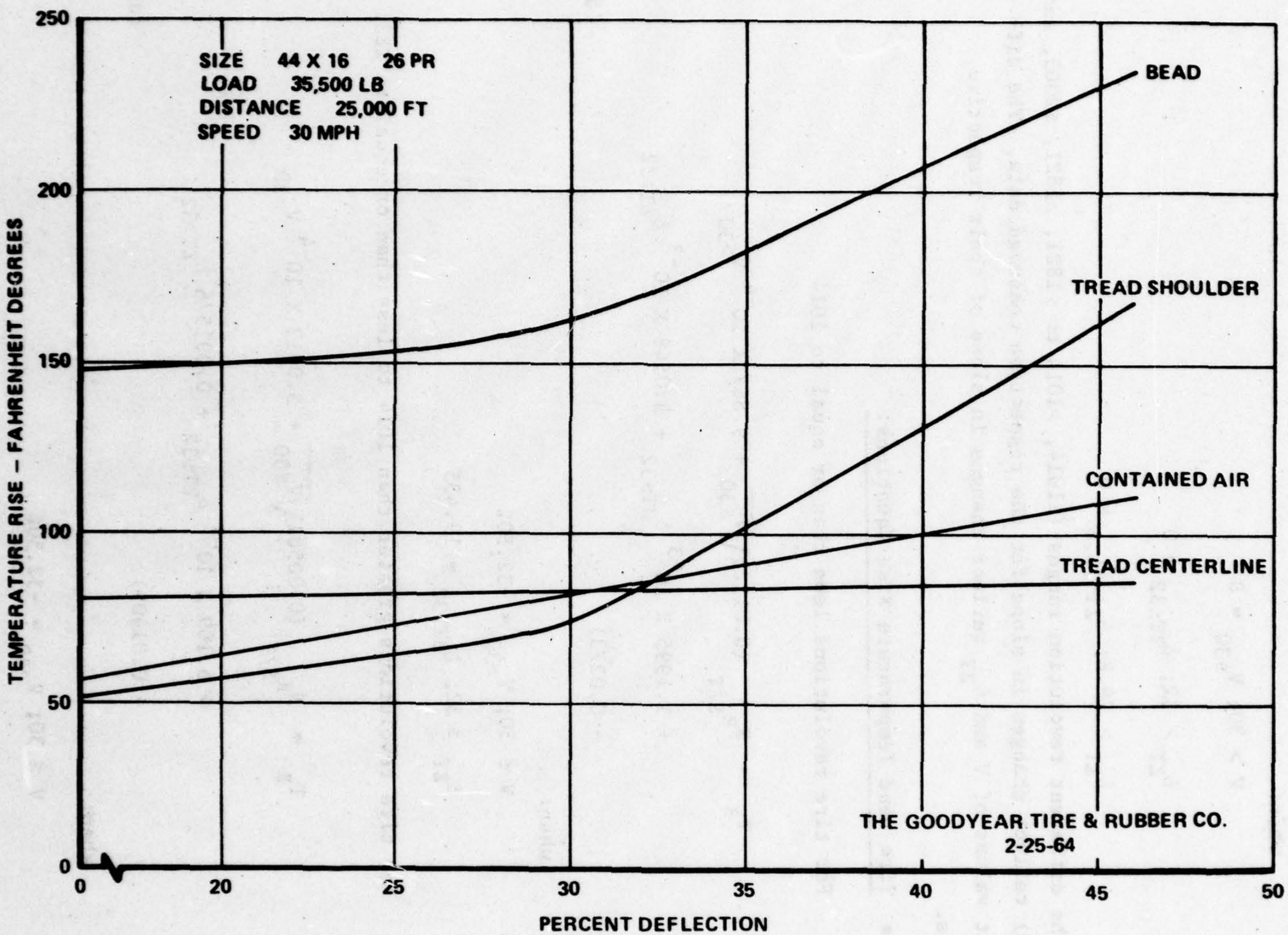


Figure 2-3. Temperature Rise Versus Percent Deflection

when:

$$V > 30;\ V_{\le 30} = 0$$

$$\delta_{ZT} > 32;\ \delta_{ZT\le 32} = 0$$

$$\delta_{ZT} > 29.8;\ \delta_{ZT\le 29.8} = 0$$

The different revolution ranges (≤1014, >1014 to ≤1821, >1821, ≤2003, and >2003) reflect changes in slope for the respective measured data. The different values of V and δ_{ZT} reflect changes in slope of their respective curves.

- <u>Tire Bead Temperature Rise Equations:</u>

For tire revolutions less than or equal to 1014

$$T_B = N_{R_{S/T}} \left(0.01126\sqrt{V_{\le 30}} + 9.867 \times 10^{-4}\, V_{>30} + 1.1995 \times 10^{-3}\, \delta_{ZT\le 32} + 3.0548 \times 10^{-3}\, \delta_{ZT>32} - 0.0273\right) \tag{5}$$

when:

$$V \le 30;\ V_{>30} = -32.502$$

$$\delta_{ZT} \le 32;\ \delta_{ZT>32} = 19.435$$

For tire revolutions greater than 1014 to less than or equal to 1821

$$T_B = N_{R_{S/T}} \left(0.00581\sqrt{V_{\le 30}} + 5.0913 \times 10^{-4}\, V_{>30} + 6.189 \times 10^{-4}\, \delta_{ZT\le 32} + 0.001576\, \delta_{ZT>32} - 0.01409\right) \tag{6}$$

when:

$$V \le 30;\ V_{>30} = -32.506$$

$$\delta_{ZT} \le 32;\ \delta_{ZT>32} = 19.442$$

For tire revolutions greater than 1821

$$T_B = N_{R_{S/T}} (0.002667\sqrt{V_{\le 30}} + 1.6562 \times 10^{-4} V_{>30}$$

$$+ 2.8405 \times 10^{-4} \delta_{ZT\le 32} + 7.2344 \times 10^{-4} \delta_{ZT>32}$$

$$- 0.004421) \tag{7}$$

when:

$V \le 30;\ V_{>30} = -59.202$

$\delta_{ZT} \le 32;\ \delta_{ZT>32} = 19.435$

- Tread Shoulder Temperature Rise Equations:

For tire revolutions less than or equal to 2003

$$T_{TS} = N_{R_{S/T}} (2.6439 \times 10^{-3} \sqrt{V_{\le 30}} + 4.2445 \times 10^{-4} V_{>30}$$

$$+ 6.5948 \times 10^{-4} \delta_{ZT\le 29.8} + 0.003412\ \delta_{ZT>29.8}$$

$$- 0.08028) \tag{8}$$

when:

$V \le 30;\ V_{>30} = -4.118$

$\delta_{ZT} \le 29.8;\ \delta_{ZT>29.8} = 24.042$

For tire revolutions greater than 2003

$$T_{TS} = N_{R_{S/T}} (0.001214 \sqrt{V_{\leq 30}} + 1.9485 \times 10^{-4} V_{>30}$$

$$+ 3.0275 \times 10^{-4} \delta_{ZT \leq 29.8} + 0.001454 \delta_{ZT > 29.8}$$

$$- 0.03352) \qquad (9)$$

when:

$V \leq 30$; $V_{>30} = -4.118$

$\delta_{ZT} \leq 29.8$; $\delta_{ZT>29.8} = 23.604$

The appendix contains coding forms for programming the equations on a Texas Instrument SR-52 calculator.

The number of tire revolutions (N_{R_S}) made by tires during straight taxi is a function of distance traveled, undeformed diameter of the tire, and percentage of tire deflection as follows:

$$N_{R_S} = \frac{1800 D_s}{\pi (150 d_O - \delta_{100} \delta_{TZ})} \qquad (10)$$

where;

D_s = Distance traveled - Feet

d_O = Undeflected tire diameter - Inches

δ_{TZ} = Tire deflection - Percent

δ_{100} = 100 percent tire deflection (section height less flange height)- Inches

The number of revolutions experienced by a given tire in a turn of 90 degrees is determined by the following equation:

$$N_{R_T} = \frac{75(12\ R_B + l_n)}{(150\ d_o - \delta_{100}\ \delta_{T_Z})} \tag{11}$$

where,

R_B = Radius of turn measured from the center of the turn to the center of the strut nearest the center of the turn - Feet

l_n = Distance from the center of the strut to the center of the tire tread - Inches

The appendix contains coding forms for programming the equations on a Texas Instrument SR-52 Calculator.

Tire bead temperatures calculated using equations (5) through (7) were compared with the corresponding measured results obtained from taxi tests performed with an airplane equipped with 50X20-20 32-ply rating tires. Figures 2-4 through 2-7 present the calculated data points plotted on curves of measured temperature rise as a function of distance traveled for various combinations of velocity and tire inflation pressure. The greatest difference in the calculated temperature when compared with the measured data is about 12 percent.

Calculated results were also compared with dynamometer tests. Table 2-4 presents the temperature rise for the measured and calculated values. Except for one run, the calculated data is within 11 percent of the measured data.

2.4.3 Tire Fatigue and Damage

Tire dynamometer test data for cyclic loading and tire failure under various loadings indicate that tire damage can occur under different combinations of load and temperature. For example, the curve of Figure 2-8 shows load for tire failure as a function of distance traveled. The calculated bead temperatures superimposed on the curve provide the following observations:

- The low loads permit long taxi distances without failure which results in tire temperature buildup. Failure at low loads can be attributed to the high temperatures which temporarily weaken the tire nylon cord material (less than 50 percent of the available strength at 75 degrees Fahrenheit) and increases the tire pressure to the point where the tire will burst.

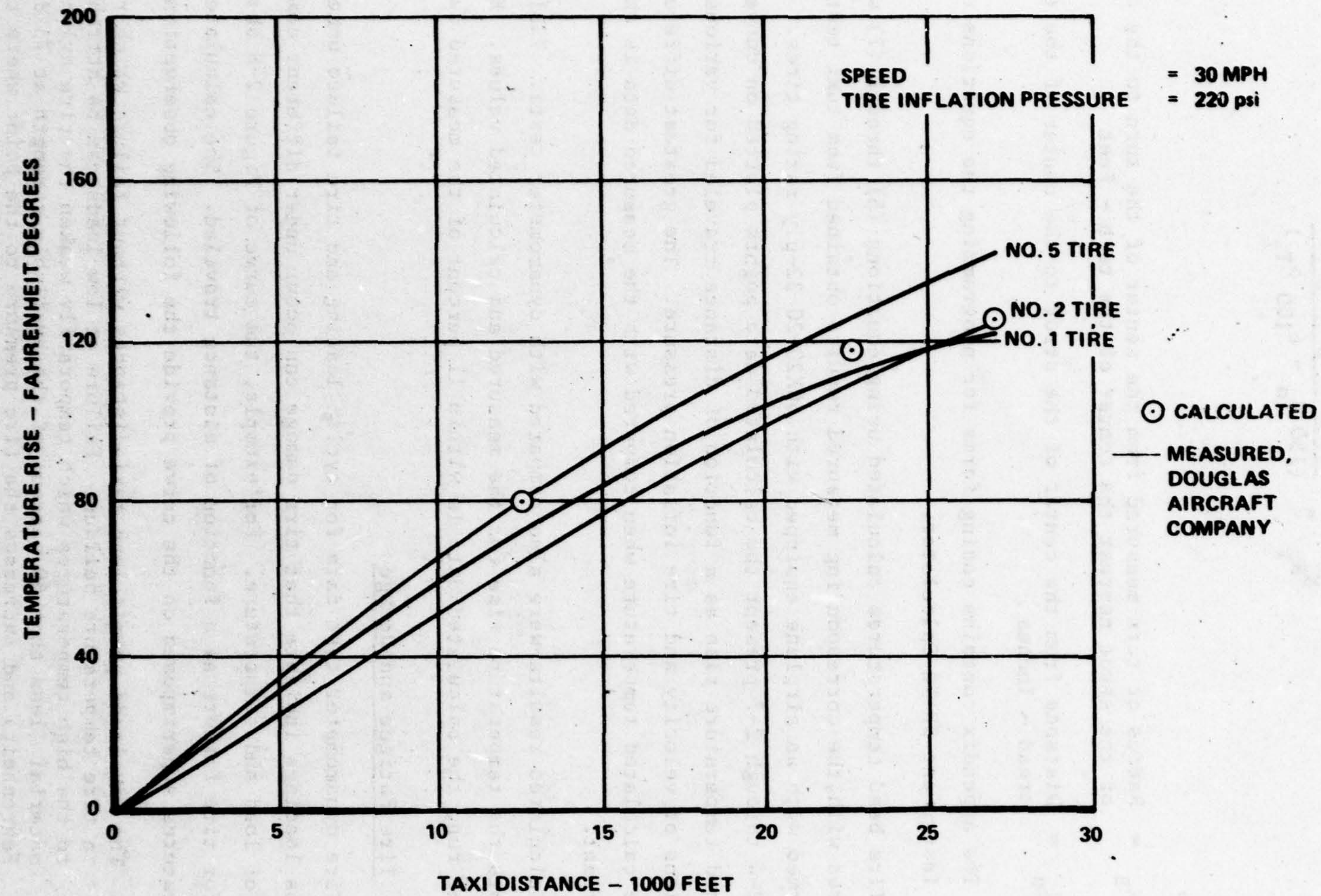


Figure 2-4. Tire Bead Temperature Rise

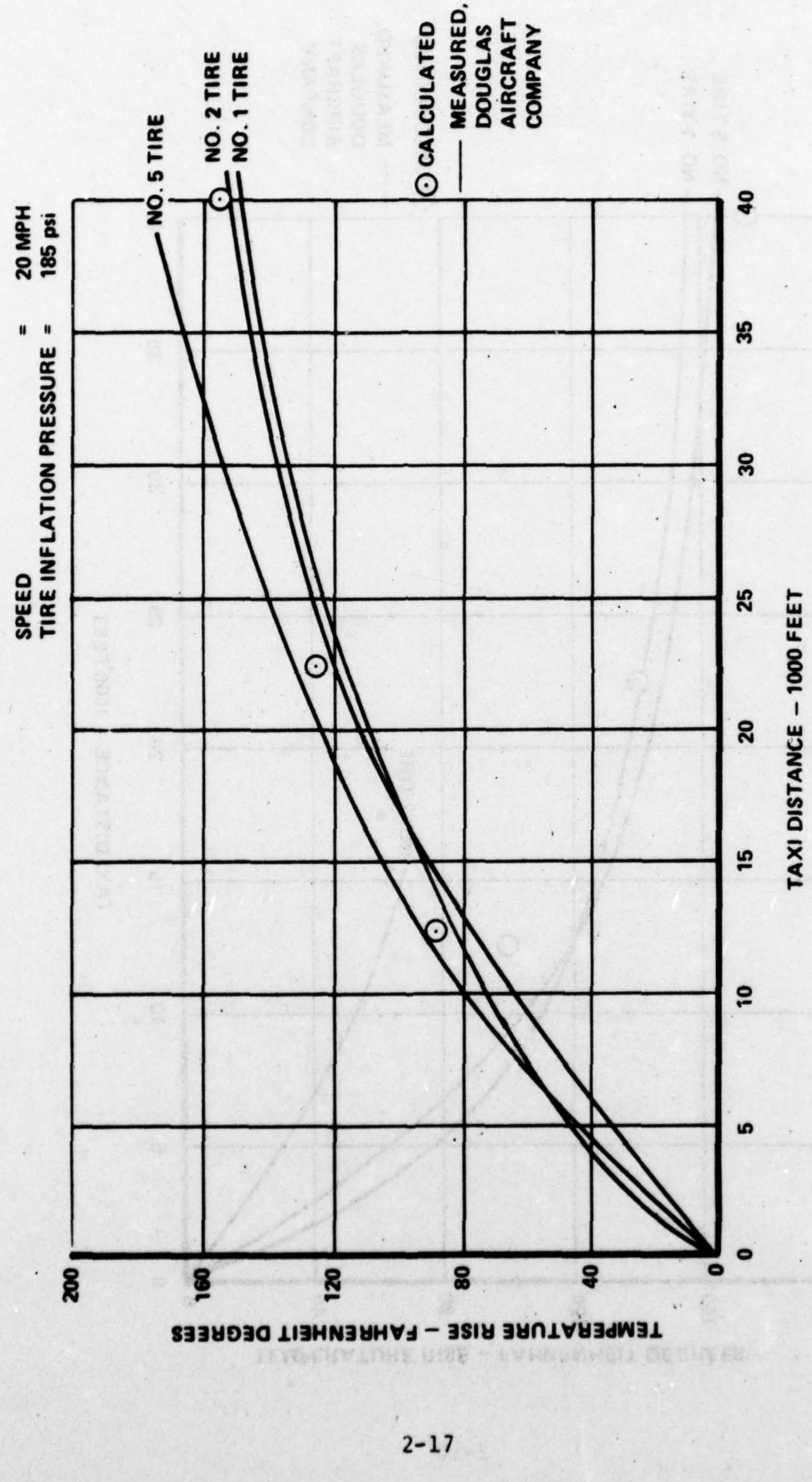


Figure 2.5. Tire Bead Temperature Rise

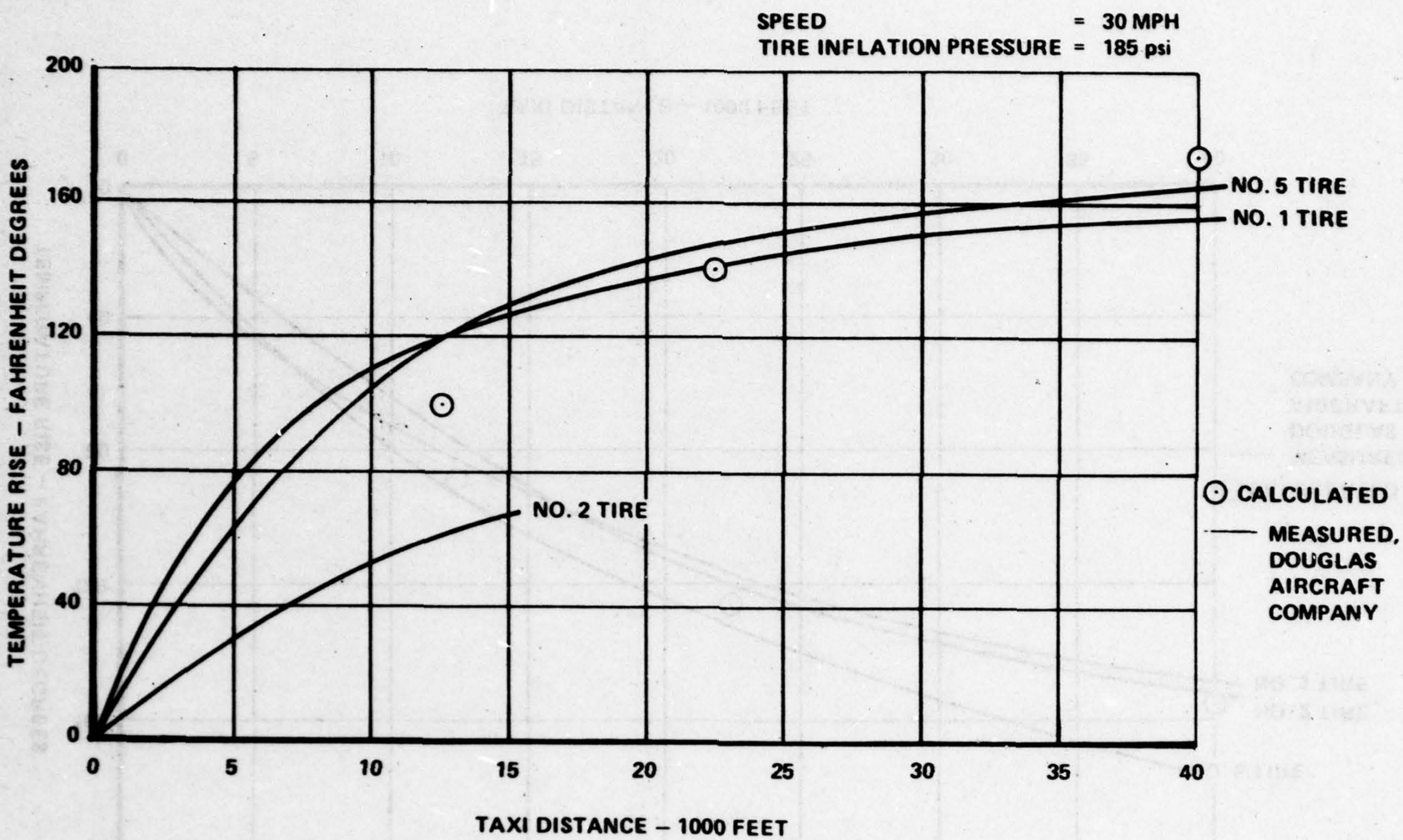


Figure 2.6. Tire Bead Temperature Rise

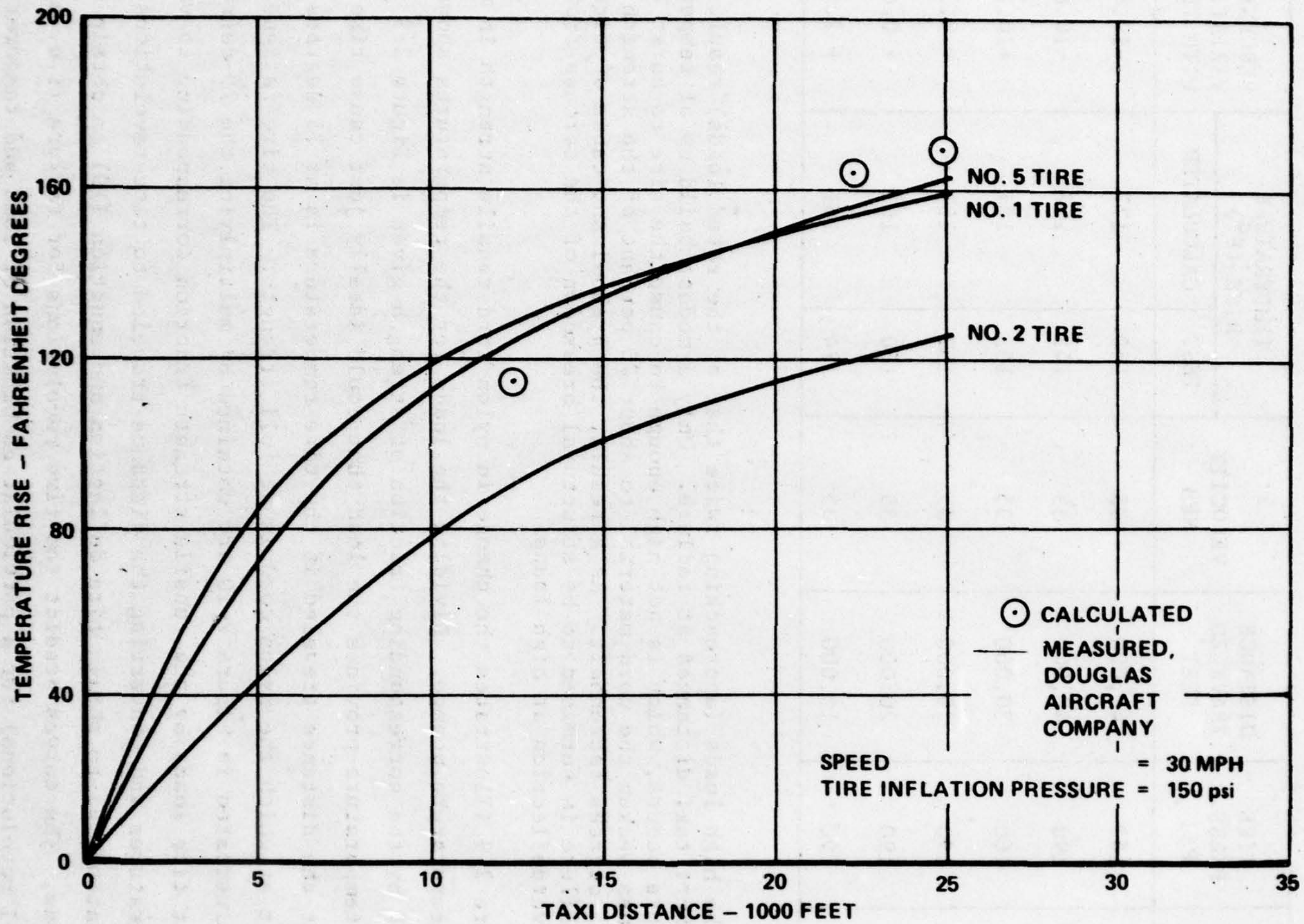


Figure 2-7. Tire Bead Temperature Rise

TABLE 2-4. TIRE BEAD TEMPERATURE RISE, DYNAMOMETER TESTS

LOAD POUNDS	TIRE PRESS. PSI	DISTANCE TRAVELED FEET	VELOCITY MPH	TEMPERATURE RISE (F^o) TEST	CALCULATED	PERCENTAGE VARIATION WITH TEST
45,300	160	40,000	35	150	177	-17.4
45,300	190	40,000	35	142	157	-10.6
53,800	160	30,000	35	155	171	-10.3
53,800	190	30,000	35	152	157	- 3.3
69,940	190	20,000	35	160	161	- 0.6
86,080	190	15,000	35	174	161	+ 7.5

- The high loads (approaching twice that of the rated loads) result in short taxi distances at failure. Only a modest build up of temperature occurs, which is not high enough to cause the tire to burst but does weaken the cord material to about 70 percent of the strength at 75 degrees Fahrenheit. As a result, the predominant cause of tire failure is surmised to be structural breakdown of the carcass from overdeflection at high loads.

Figure 2-9 illustrates the change in nylon cord tensile strength in relation to temperature change. Dividing the loads for the temperatures shown in Figure 2-8 by the corresponding fraction of strength given in Figure 2-9 for the same temperature provides the load that could ideally just cause tire failure at the distance traveled if the tire temperature is at 75 degrees Fahrenheit at which the nylon cord is at full strength. The tire fatigue curves illustrated in Figure 2-10 are obtained by multiplying the 75-degree Fahrenheit tire loads by the tensile strength fraction corresponding to various temperatures and converting the distance traveled to tire revolutions, using equation (4) to obtain tire deflection and equation (10) to obtain tire revolutions. The curves predict the tire revolutions for failure (i.e. allowable total revolutions) for a particular combination of load and temperature.

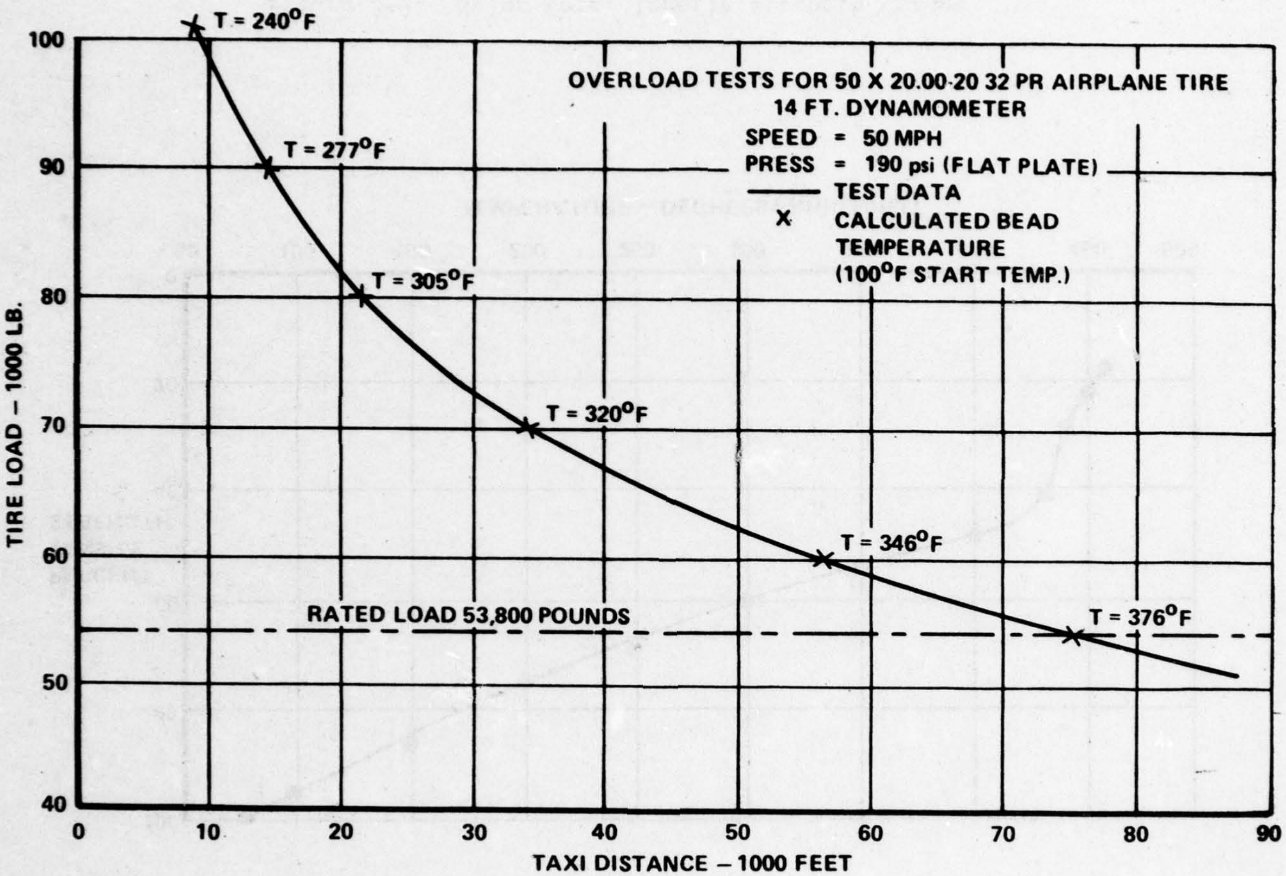


Figure 2-8. Tire Failure Distance Versus Temperature and Load

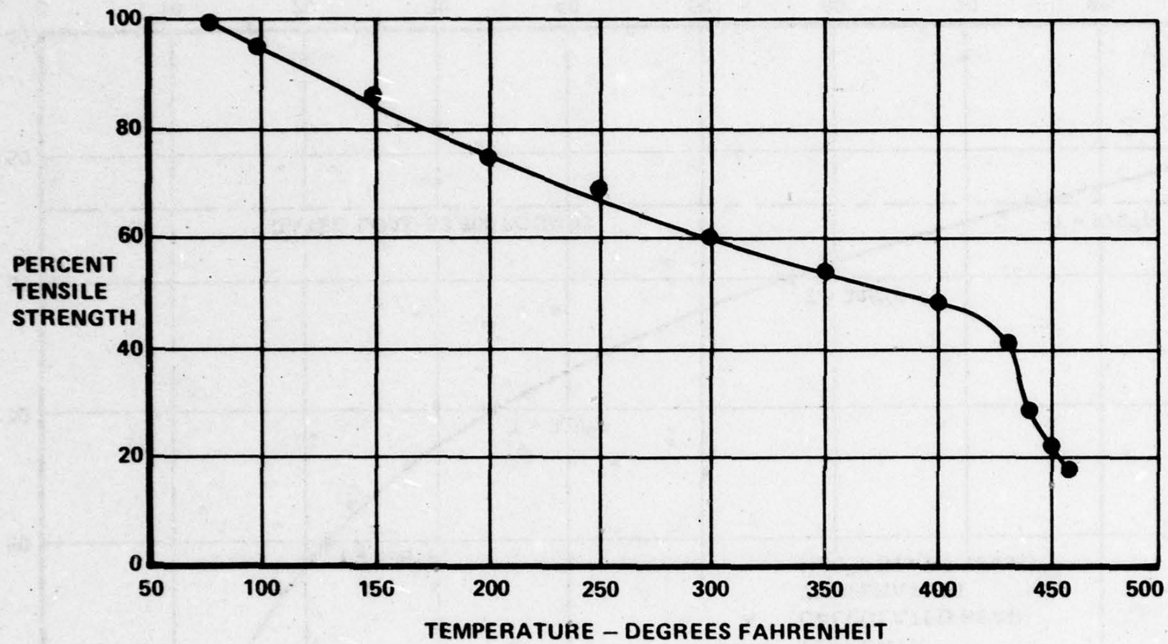


Figure 2-9. Nylon Cord, Tensile Strength Change as a Function of Temperature Change

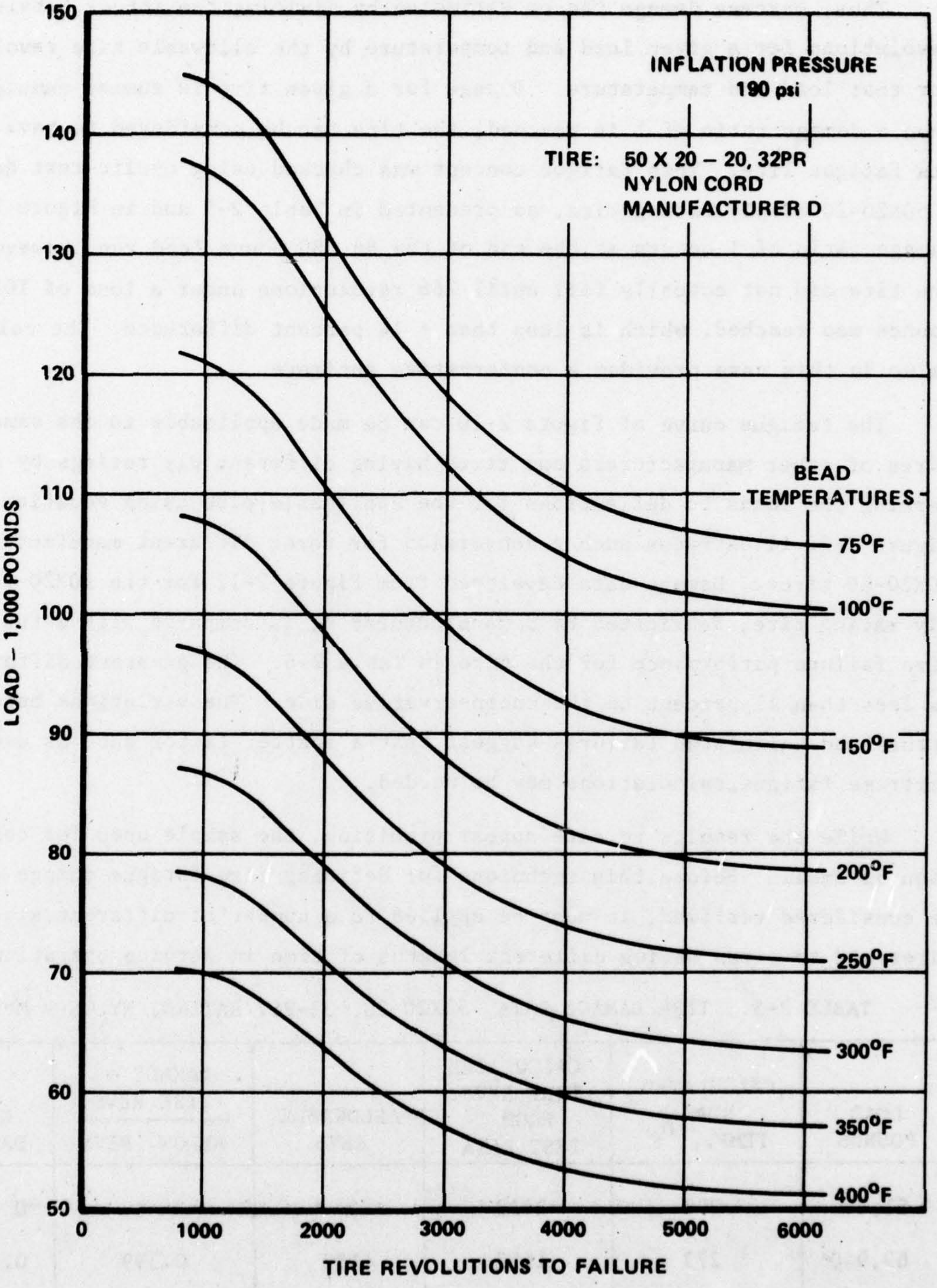


Figure 2-10. Tire Fatigue Curve

Thus, carcass damage can be estimated by dividing the actual service tire revolutions for a given load and temperature by the allowable tire revolutions for that load and temperature. Damage for a given tire is summed cumulatively. When a damage ratio of 1 is reached, the tire can be considered to have reached its fatigue life. This fatigue concept was checked using cyclic test data of a 50X20-20 32-ply rating tire, as presented in Table 2-5 and in Figure 2-11. Damage ratio of 1 occurs at the end of the 86,080 pound load run; however, the tire did not actually fail until 266 revolutions under a load of 102,220 pounds was reached, which is less than a 14 percent difference. The calculated value in this case provides a conservative estimate.

The fatigue curve of Figure 2-10 can be made applicable to the same size tires of other manufacturers and tires having different ply ratings by converting the loads to deflections for the applicable tire using equation (4). Figure 2-12 illustrates such a conversion for three different manufacturer's 50X20-20 tires. Damage data developed from Figure 2-12 for the 50X20-20, 32 ply rating tire, fabricated by a manufacturer A, is compared with actual tire failure performance for the tire in Table 2-6. The greatest difference is less than 11 percent on the unconservative side. The variations between actual and calculated failures suggest that a scatter factor such as used in airframe fatigue calculations may be needed.

While the results to date appear promising, the sample used for correlation is small. Before this technique for defining tire fatigue damage can be considered verified, it must be applied to a number of different size tires and to tires having different lengths of time in service operations.

TABLE 2-5. TIRE DAMAGE DATA, 50X20-20, 32-PLY RATING, NYLON - MFG'R D

LOAD POUNDS	CALCULATED BEAD TEMP., °F	CALCULATED TIRE REVS. FROM TEST DATA	ALLOWABLE REVS	DAMAGE = TIRE REVS / ALLOW. REVS	CUM. DAMAGE
53,800	290	2450	∞	0	0
69,940	272	1657	4150	0.399	0.399
86,080	263	1259	1950	0.646	1.045
102,220	144	266	2900	0.092	1.137

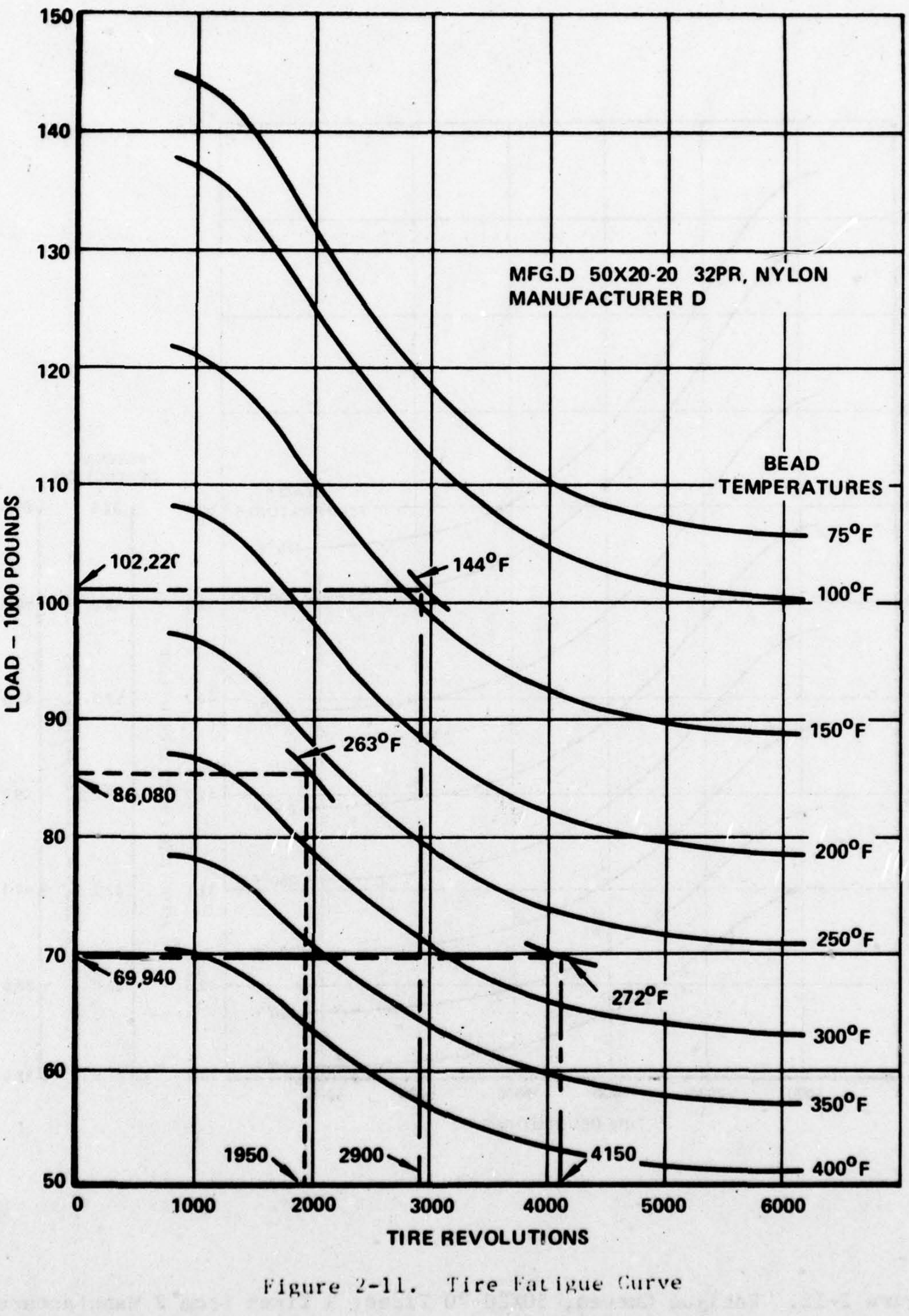


Figure 2-11. Tire Fatigue Curve

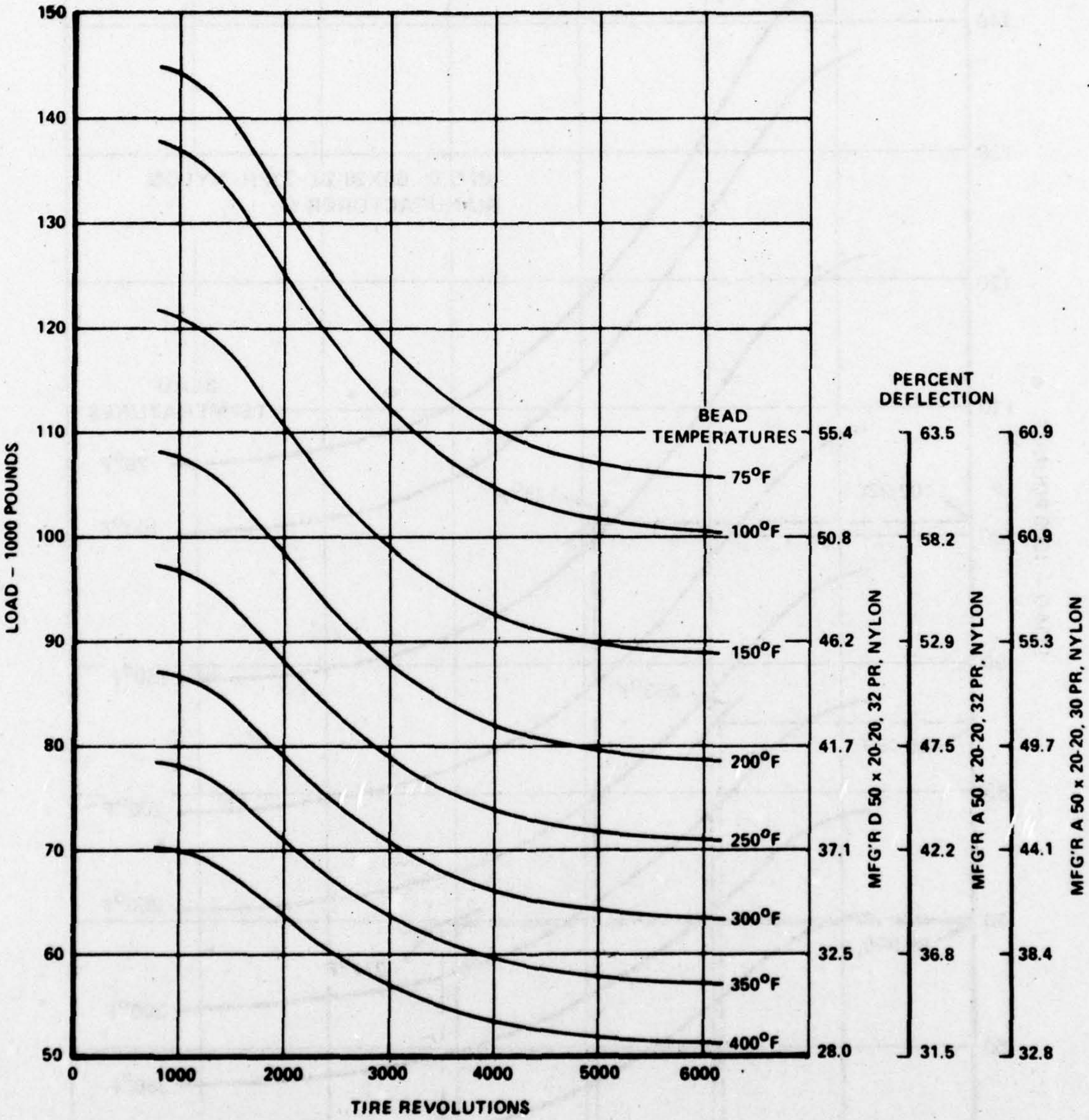


Figure 2-12. Fatigue Curves, 50X20-20 Tires, 3 Tires from 2 Manufacturers

TABLE 2-6. TIRE FAILURE DATA, 50X20-20, 32-PLY RATING, MFG'R A

LOAD POUNDS	TIRE PRESSURE PSI	CALCULATED BEAD TEMP., °F	CALCULATED TIRE REVS. FROM TEST DATA	FATIGUE ALLOWABLE REVS	DAMAGE TIRE REVS / ALLOW. REVS
86,080	190	288	1291	1430	0.903
53,800	130	320	2442	2400	1.018

2.5 DETERMINATION OF CRITICAL TIRE FAILURE CONDITIONS

The results of the statistical and analytical evaluations were combined to establish tire overload scenarios for the main and nose landing gear tires. Critical points in the ground operation, as determined from the statistical evaluation, were used as the starting point for the overload condition. In addition, effects of mismatched tires, such as worn tires, tires of different manufacturers, and different inflation pressures were evaluated as to their implications on a tire that may become overloaded.

In order to evaluate the probability of encountering conditions that may cause tire fatigue damage, a typical commercial transport mission mix was used to establish airplane weight and percentage of flights at that weight. Studies were also made of maximum takeoff gross weight cases.

2.5.1 Tire Ground Operations Scenarios

The scenarios described in Table 2-7 have been chosen to illustrate tire load variation with turns, braking, runway crown, and spoiler/flap deployment. The corresponding tire temperatures and, in some cases, tire damage are also shown. The velocities employed in calculating the temperature rises for the scenarios are as follows:

All turns = 10 MPH

Straight taxi = 25 MPH

Average takeoff, landing braking, and RTO $\frac{140 \times 1.152}{2} = 80$ MPH

Landing Roll = 130 X 1.152 = 150 MPH

Figures 2-13 through 2-16 illustrate the effect on tire deflection and temperature of using rated pressure (irrespective of takeoff weight) as opposed to adjusting the tire pressure to provide a deflection of 32 percent for a given takeoff weight. In all four cases, turns have only a minor effect on both tire deflection and cumulative tire temperature. There is a noticeable difference in tire deflection and cumulative tire temperature between operations in which tires are inflated to rated pressure, as compared to pressure adjusted to 32-percent tire deflection (compare Figures 2-13 and 2-15 with 2-14 and 2-16, respectively).

Figures 2-17 and 2-18 present scenarios for a dual-tandem landing gear configured airplane depicting a failed tire occurring immediately prior to takeoff followed by an RTO for tires having rated pressure and adjusted pressure, respectively. The significance of using rated pressure for safety reasons is demonstrated. In the case where the tire is inflated to a pressure for a deflection of 32 percent, the tire deflection is well above the value for which tire failure is expected to occur. On the other hand, the overloaded tire at rated pressure sustained some fatigue damage in the RTO and subsequent taxi to the ramp but did not fail.

Figures 2-19 through 2-24 are the corresponding scenarios for the dual main gear configured airplanes. While individual parameter values may vary the trends are essentially the same except for lateral loads during turns. Accordingly, the landing gear configuration is not a factor to consider in developing tire overload capability. The statistical summaries given in Tables 2-1 and 2-2 support this position.

The effect of landing roll and taxi on tire deflection and temperature with one tire flat on a dual-tandem and dual main gear configured airplanes are illustrated in Figures 2-25 through 2-28. Tire fatigue damage calculations indicate that when rated pressure is used, the overloaded tire will not fail including taxi to the ramp. In both cases in which the pressure has been adjusted for a tire deflection of 32 percent, tire failure occurs after the airplane slows to taxi speeds. These results appear consistent with the low percentage of multiple tire failures encountered during landing roll and taxi to the ramp (see Table 2-2).

Nose wheel tire loads, deflections and temperature information are given in Figure 2-29 for a normal takeoff and landing. All deflections are below 29 percent and tire heat does not exceed 255-degrees Fahrenheit assuming an initial tire temperature of 100-degrees Fahrenheit for takeoff and 50-degrees Fahrenheit for landing. However, during an RTO with one flat tire (Figure 2-30), the overloaded tire deflection reached 76 percent during hard braking which can result in tire failure.

A review of the single nose gear tire failure statistics indicates that all seven failures occurred during the takeoff run. Of the seven that occurred during the takeoff run, three were followed by takeoffs and landings without further nose tire failure, one was followed by an RTO without further nose tire failure, and three lacked information regarding subsequent events. Four cases of two tire failures occurred. In two cases, both tires failed during the takeoff runs which were followed by RTO's. In one case, both tires failed during an RTO and the final case involved an extremely hard landing. The calculated low tire deflections and temperatures encountered by the nose gear tires during normal operations appear to explain the low failure rate found in the statistical data. Since all but one of the failures occurred during takeoff, self-generated heat appears to be the greatest cause of nose gear tire failures.

TABLE 2-7. INDEX OF SCENARIOS

FIGURE NUMBER	OPERATION			GEAR CONFIGURATION			AIRPLANE WEIGHT (1)	FATIGUE DAMAGE VALUE (2)	TIRE FAILED (3)	PRESSURE	
	TAKEOFF	LANDING	RTO	DUAL	DUAL-TANDEM	NOSE				RATED	ADJUSTED (4)
2-13	X	X			X		96			X	
2-14	X	X			X		96				X
2-15	X	X			X		75			X	
2-16	X	X			X		75				X
2-17	X		X		X		85	X	X	X	
2-18	X		X		X		85	X	X		X
2-19	X	X		X			96			X	
2-20	X	X		X			96				X
2-21	X	X		X			75			X	
2-22	X	X		X			75				X
2-23	X		X	X			79	X	X	X	
2-24	X		X	X			79	X	X		X
2-25		X			X		81	X	X	X	
2-26		X			X		81	X	X		X
2-27		X		X			81	X	X	X	
2-28		X		X			81	X	X		X
2-29	X	X				X	96			X	
2-30	X		X			X	96		X	X	

(1) Percent of design takeoff

(2) Left rear tire or left tire, left strut

(3) Right rear tire or right tire, left strut

(4) Tire inflation pressure adjusted to provide 32 percent deflection at takeoff gross weight

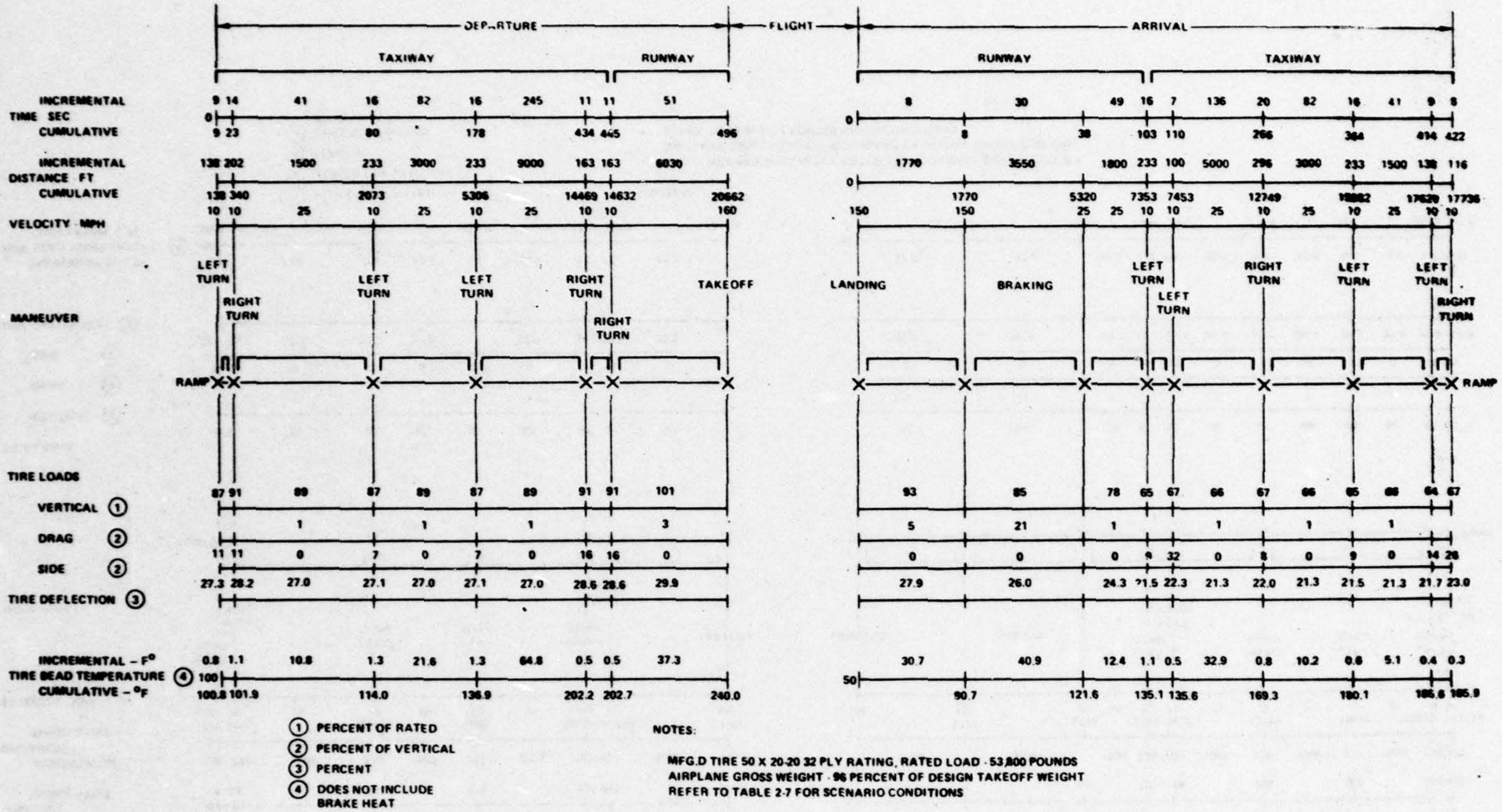


Figure 2-13. Takeoff and Landing Scenario: Dual-Tandem Gear, Right Rear Tire on Left Strut, Moderately Heavy Gross Weight, Rated Pressure

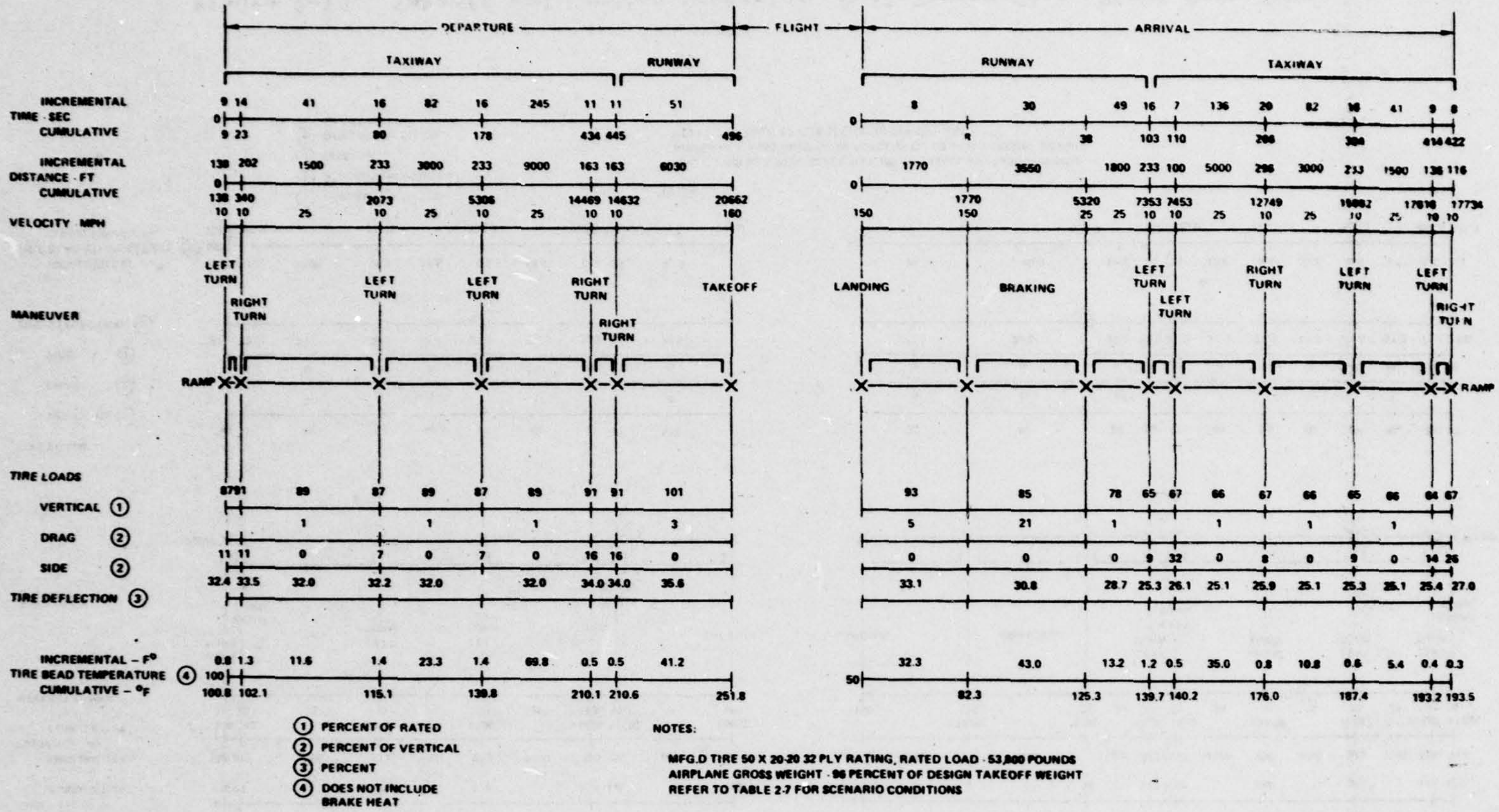


Figure 2-14. Takeoff and Landing Scenario: Dual-Tandem Gear, Right Rear Tire On Left Strut, Moderately Heavy Gross Weight, Adjusted Pressure

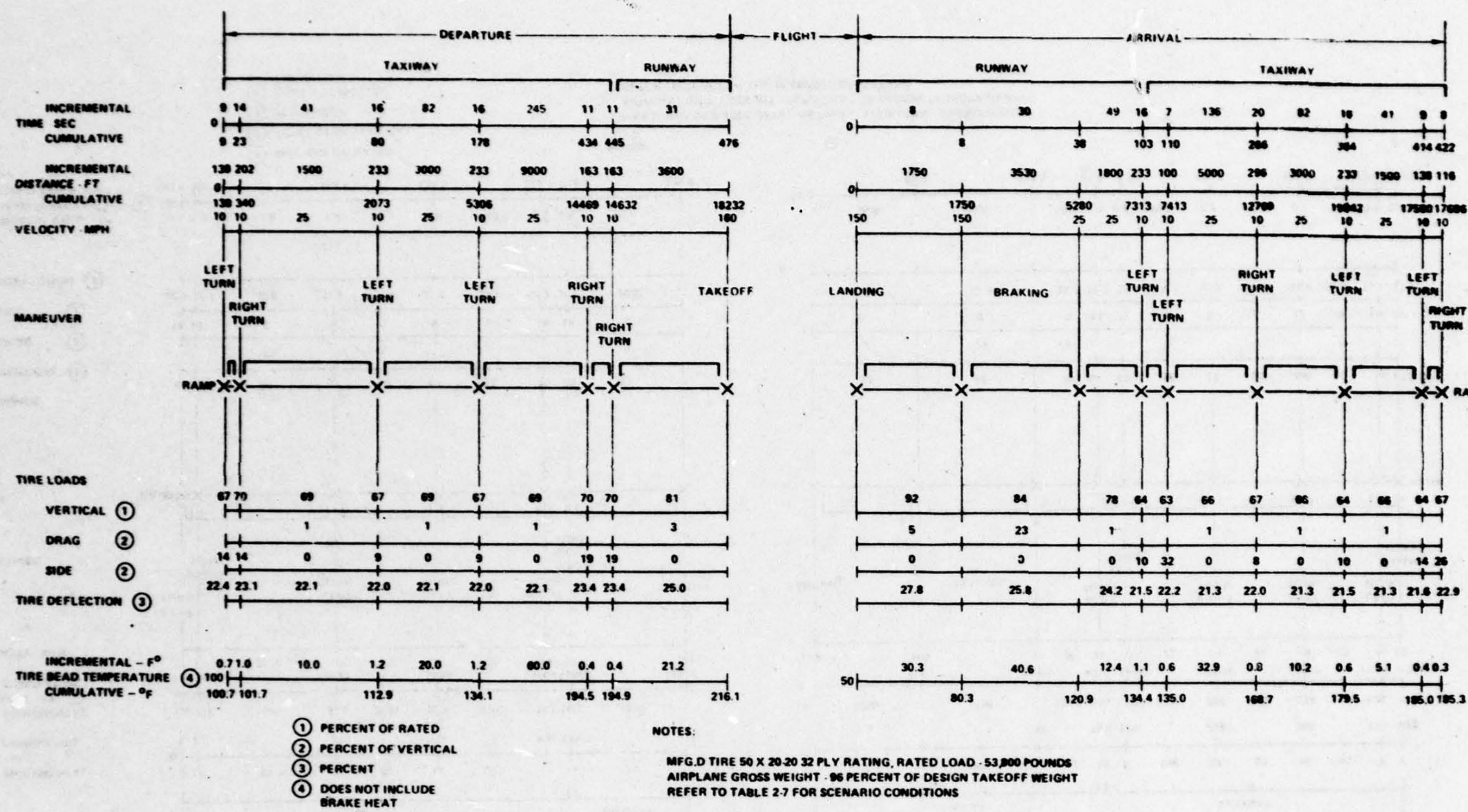
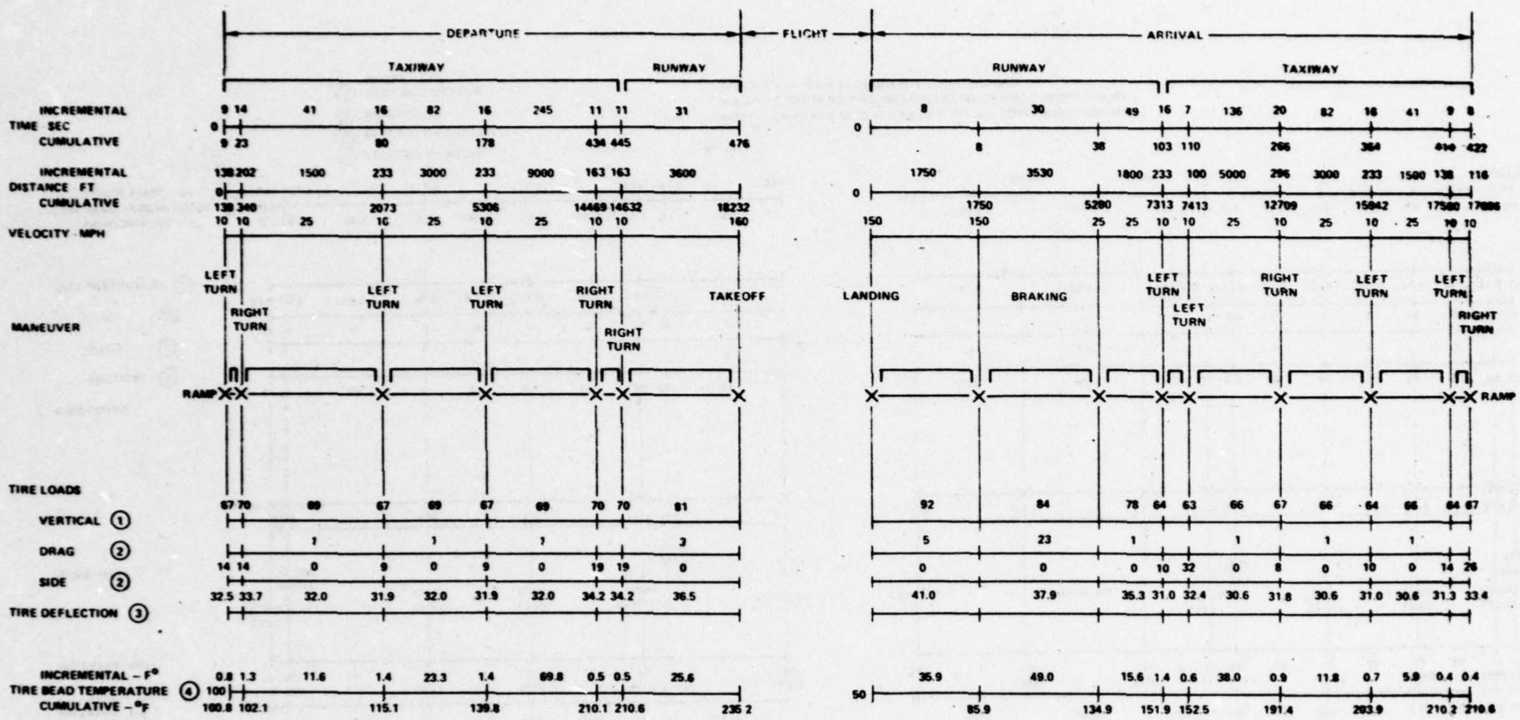


Figure 2-15. Takeoff and Landing Scenario: Dual-Tandem Gear, Right Rear Tire on Left Strut, Light Gross Weight, Rated Pressure

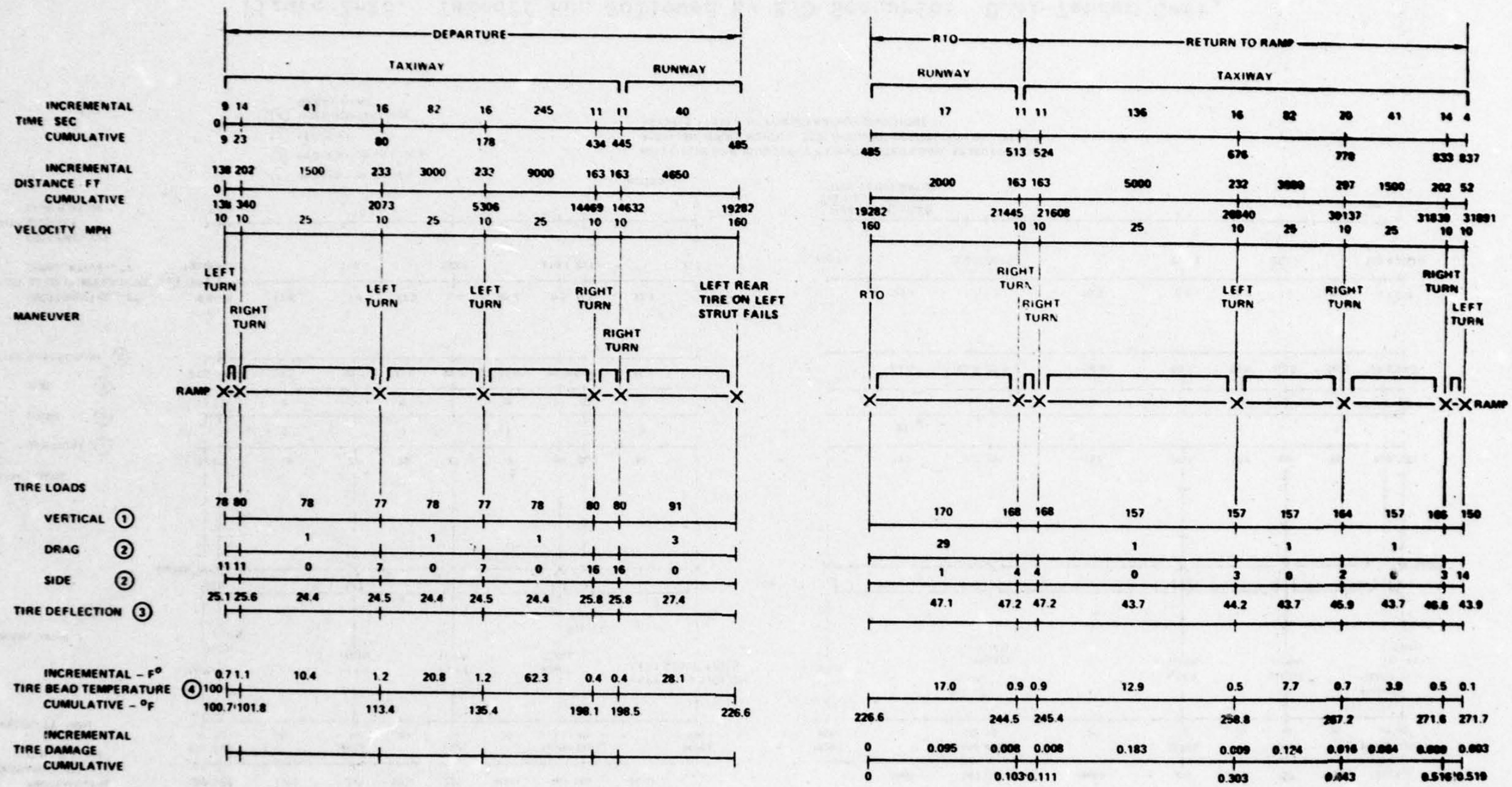


① PERCENT OF RATED
② PERCENT OF VERTICAL
③ PERCENT
④ DOES NOT INCLUDE BRAKE HEAT

NOTES:

MFG.D TIRE 50 X 20-20 32 PLY RATING, RATED LOAD 53,800 POUNDS
AIRPLANE GROSS WEIGHT · 75 PERCENT OF DESIGN TAKEOFF WEIGHT
REFER TO TABLE 2-7 FOR SCENARIO CONDITIONS

Figure 2-16. Takeoff and Landing Scenario: Dual-Tandem Gear, Right Rear Tire On Left Strut, Light Gross Weight, Adjusted Pressure



① PERCENT OF RATED
② PERCENT OF VERTICAL
③ PERCENT
④ DOES NOT INCLUDE BRAKE HEAT

NOTES:

MFG.D TIRE 50 X 20-20 32 PLY RATING, RATED LOAD - 53,800 POUNDS
AIRPLANE GROSS WEIGHT - 85 PERCENT OF DESIGN TAKEOFF WEIGHT
REFER TO TABLE 2 7 FOR SCENARIO CONDITIONS

Figure 2-17. Takeoff Run Followed by RTO Scenario: Dual-Tandem Gear, Typical Takeoff Gross Weight, Rated Pressure, Right Rear Tire On Left Strut Overloaded During RTO

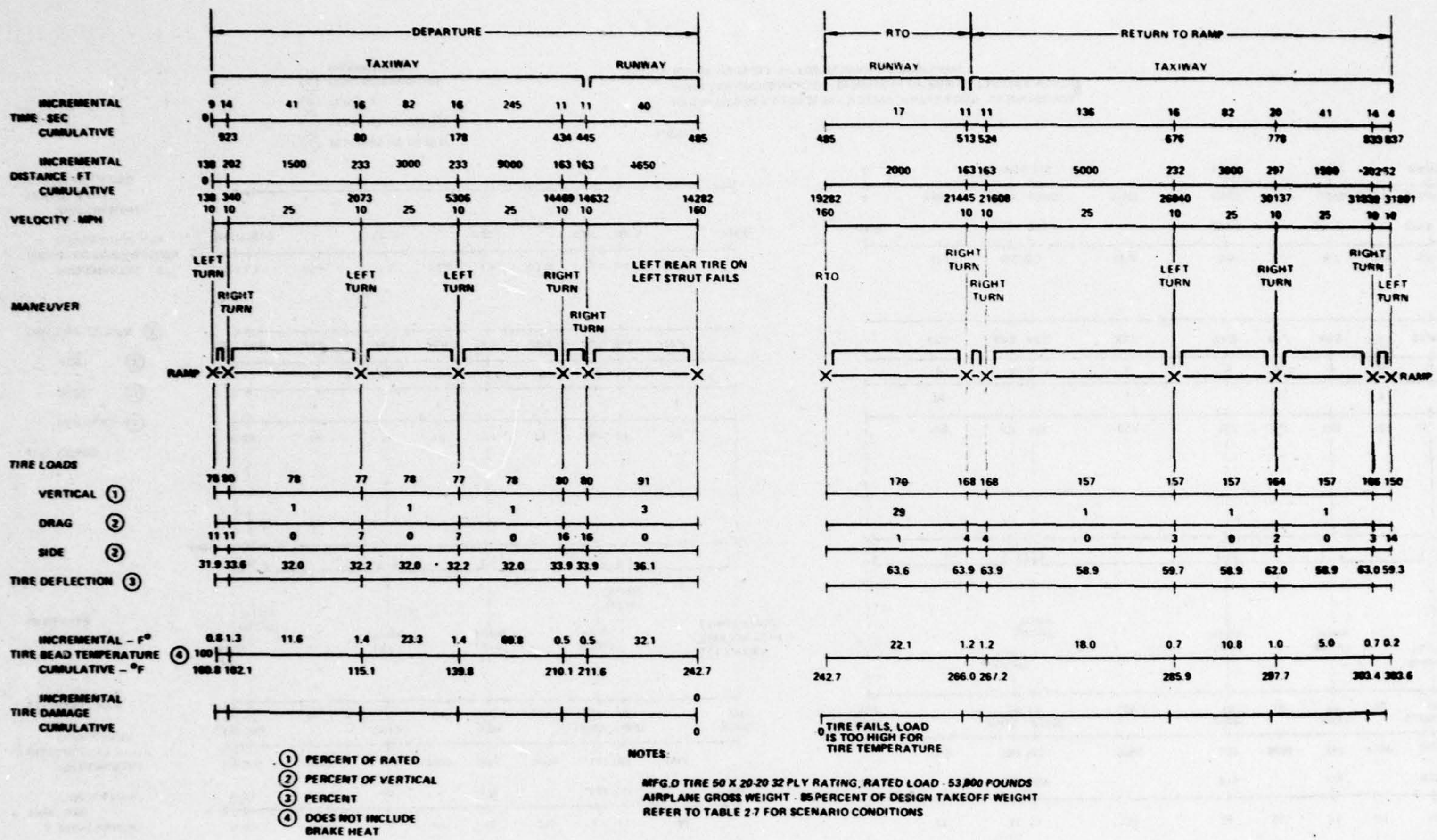


Figure 2-18. Takeoff Run Followed by RTO Scenario: Dual-Tandem Gear, Typical Takeoff Gross Weight, Adjusted Pressure, Right Rear Tire On Left Strut Overloaded/Fails During RTO

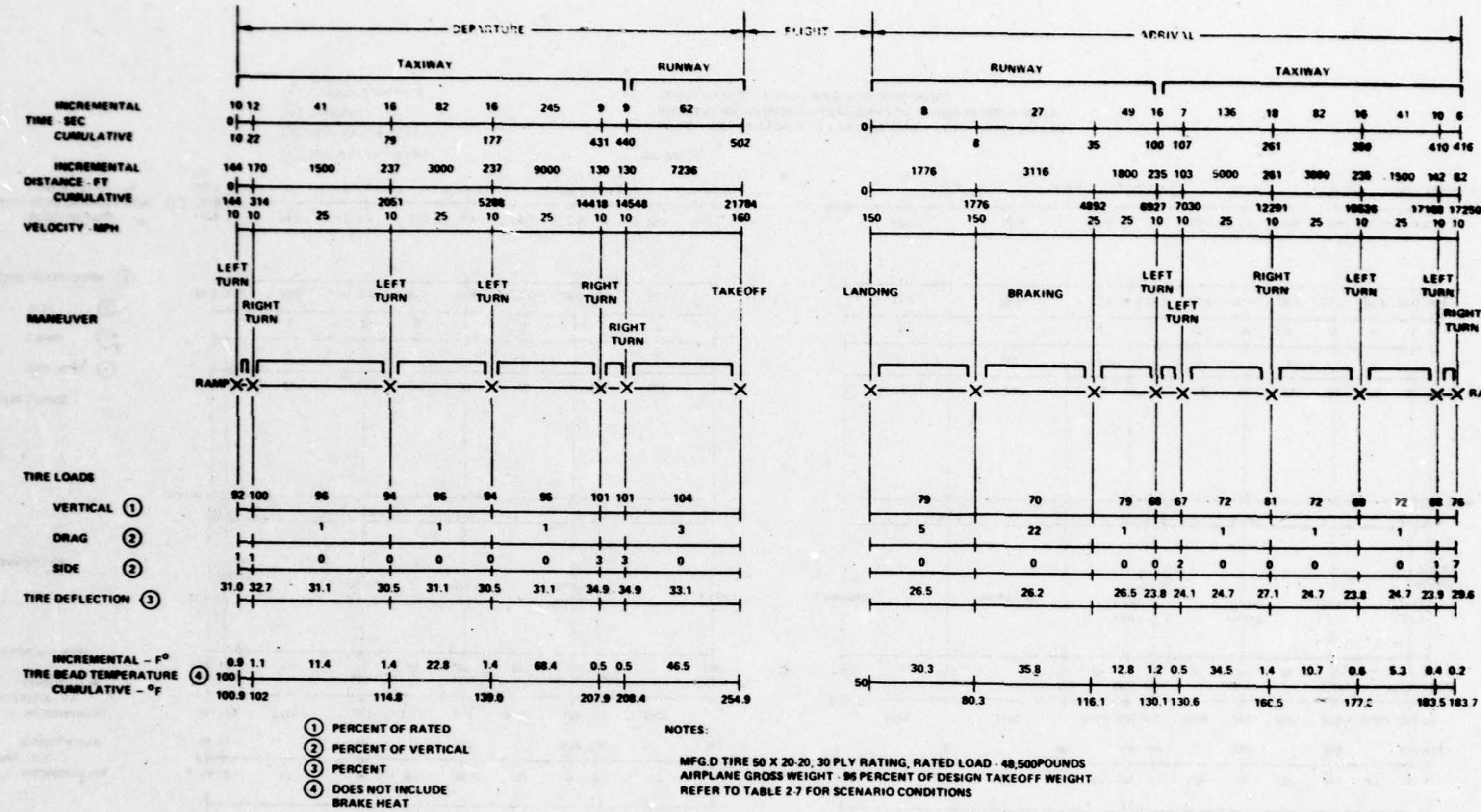


Figure 2-19. Takeoff and Landing Scenario: Dual Gear, Right Tire On Left Strut, Moderately Heavy Gross Weight, Rated Pressure

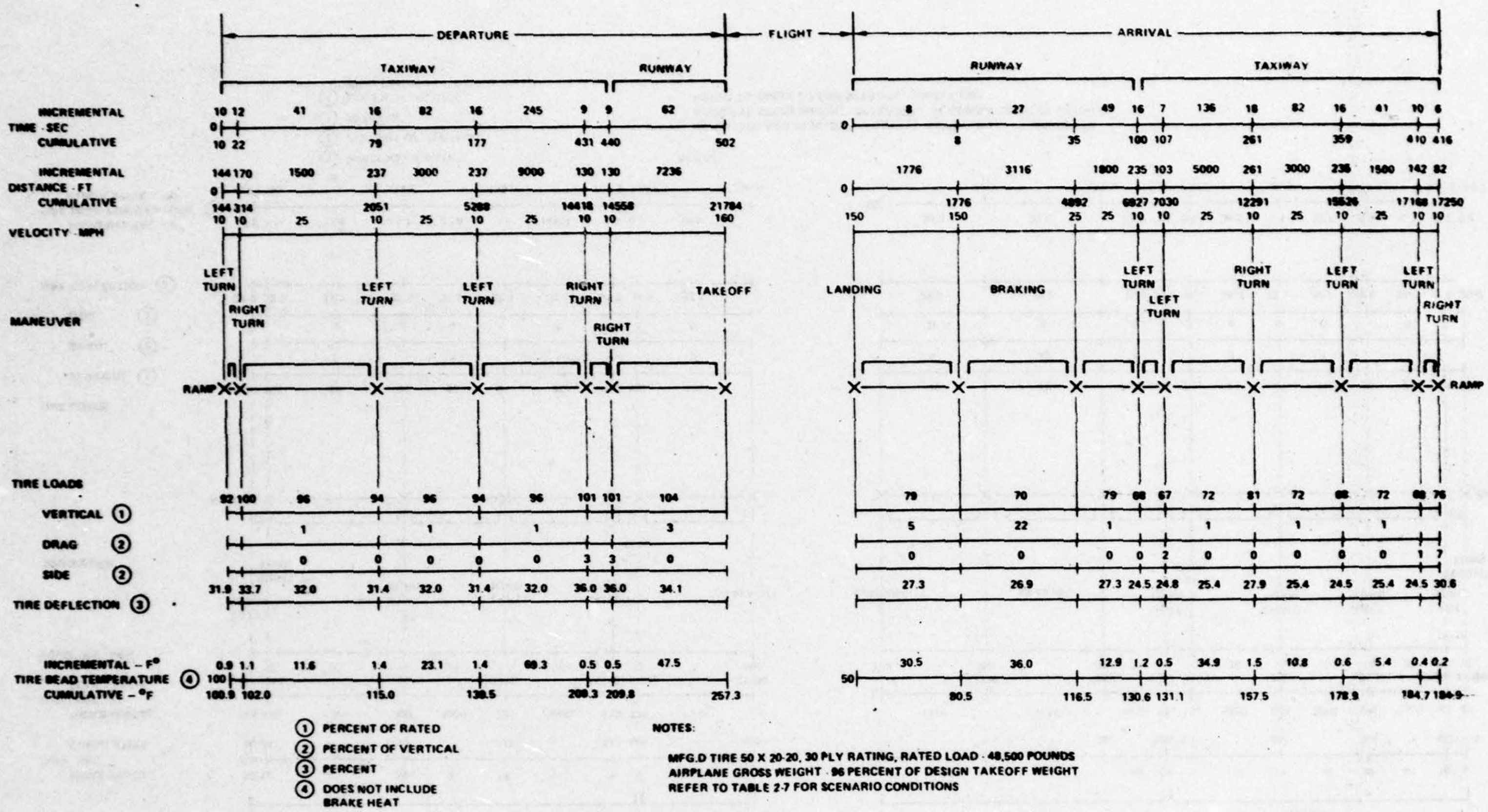


Figure 2-20. Takeoff and Landing Scenario: Dual Gear, Right Tire On Left Strut, Moderately Heavy Gross Weight, Adjusted Pressure

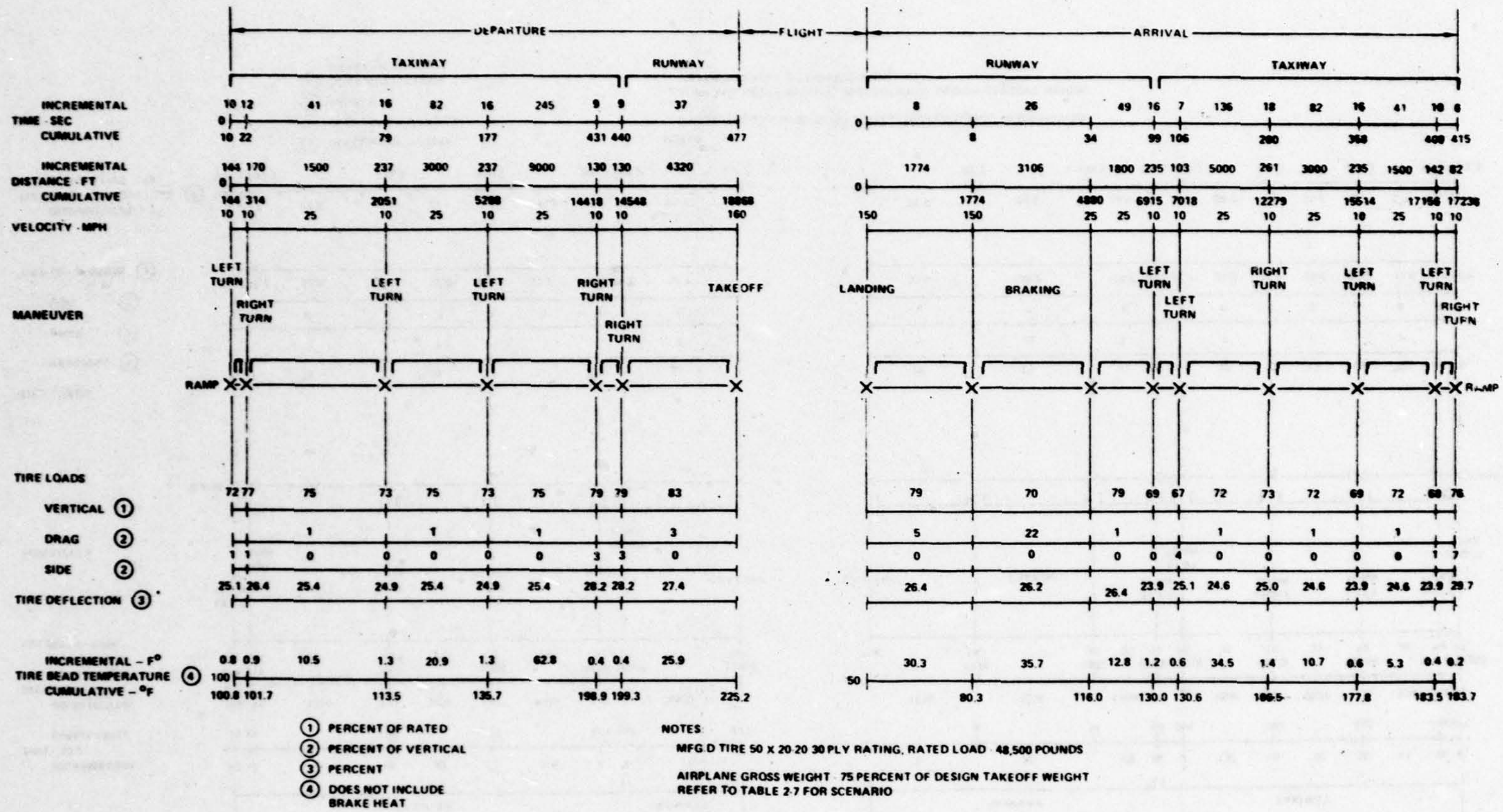


Figure 2-21. Takeoff and Landing Scenario: Dual Gear, Right Tire on Left Strut, Light Gross Weight, Rated Pressure

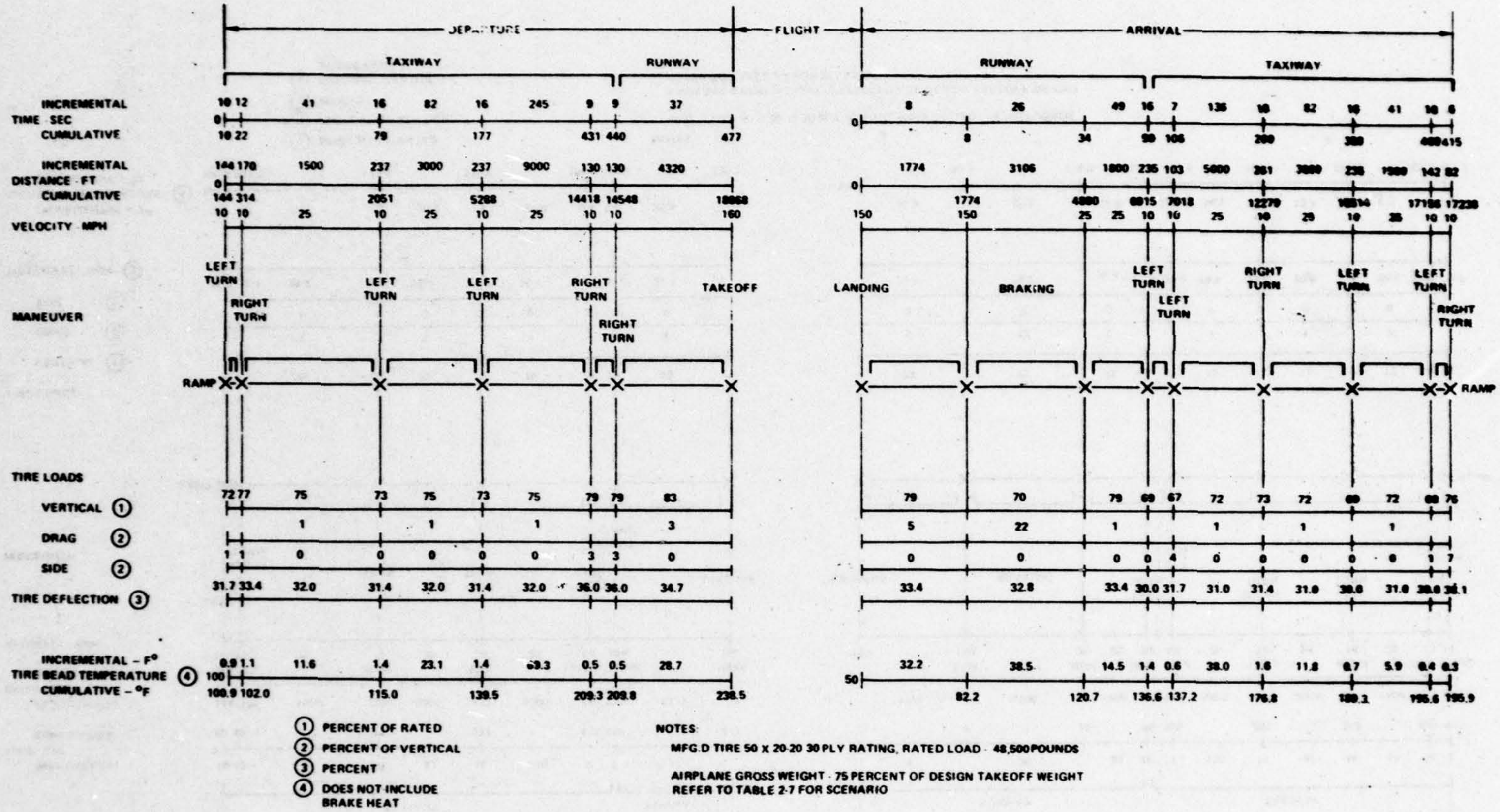


Figure 2-22. Takeoff and Landing Scenario: Dual Gear, Right Tire on Left Strut, Light Gross Weight, Adjusted Pressure

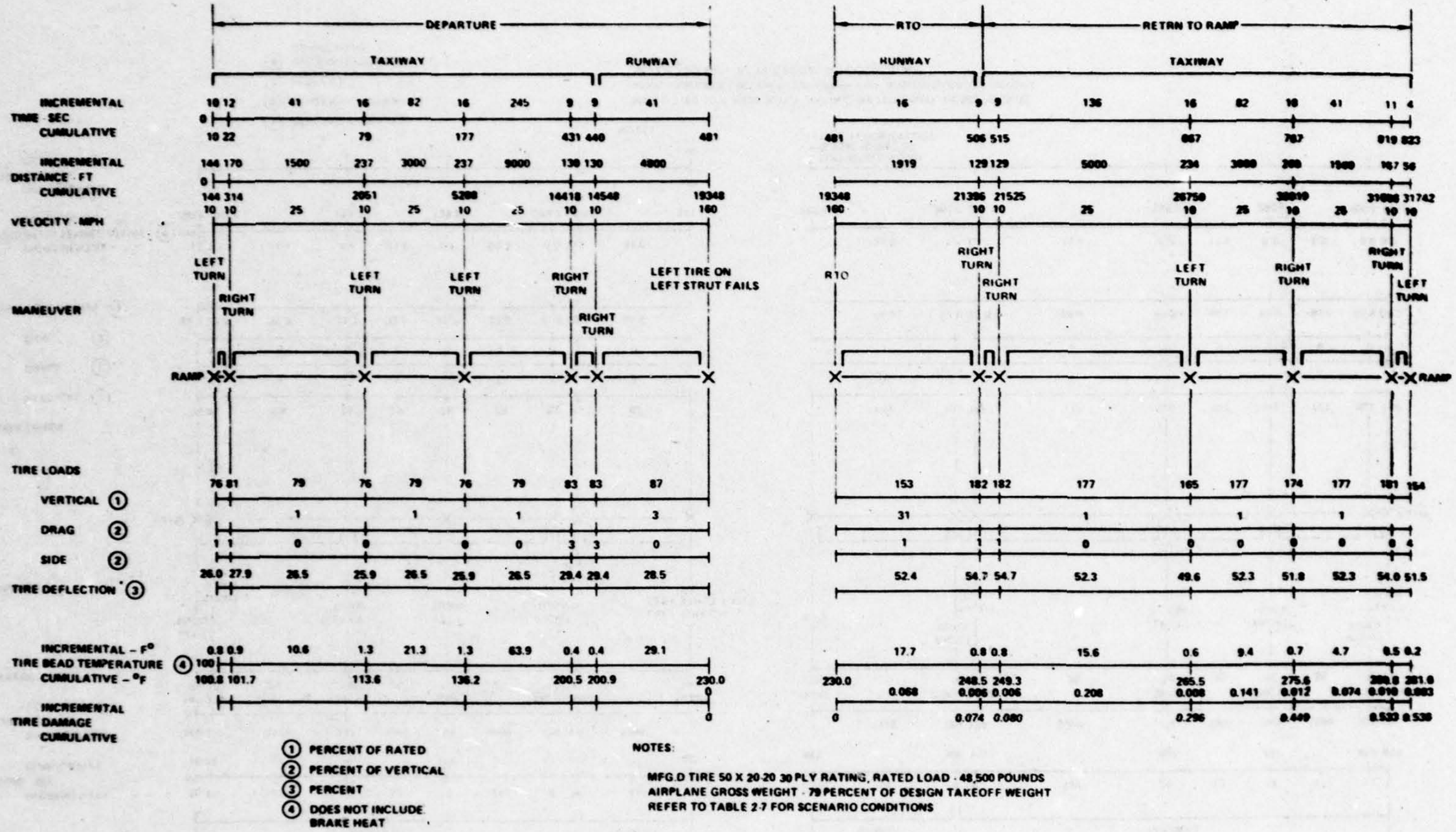


Figure 2-23. Takeoff Run Followed by RTO Scenario: Dual Gear, Typical Takeoff Gross Weight, Rated Pressure, Right Tire on Left Strut Overloaded During RTO

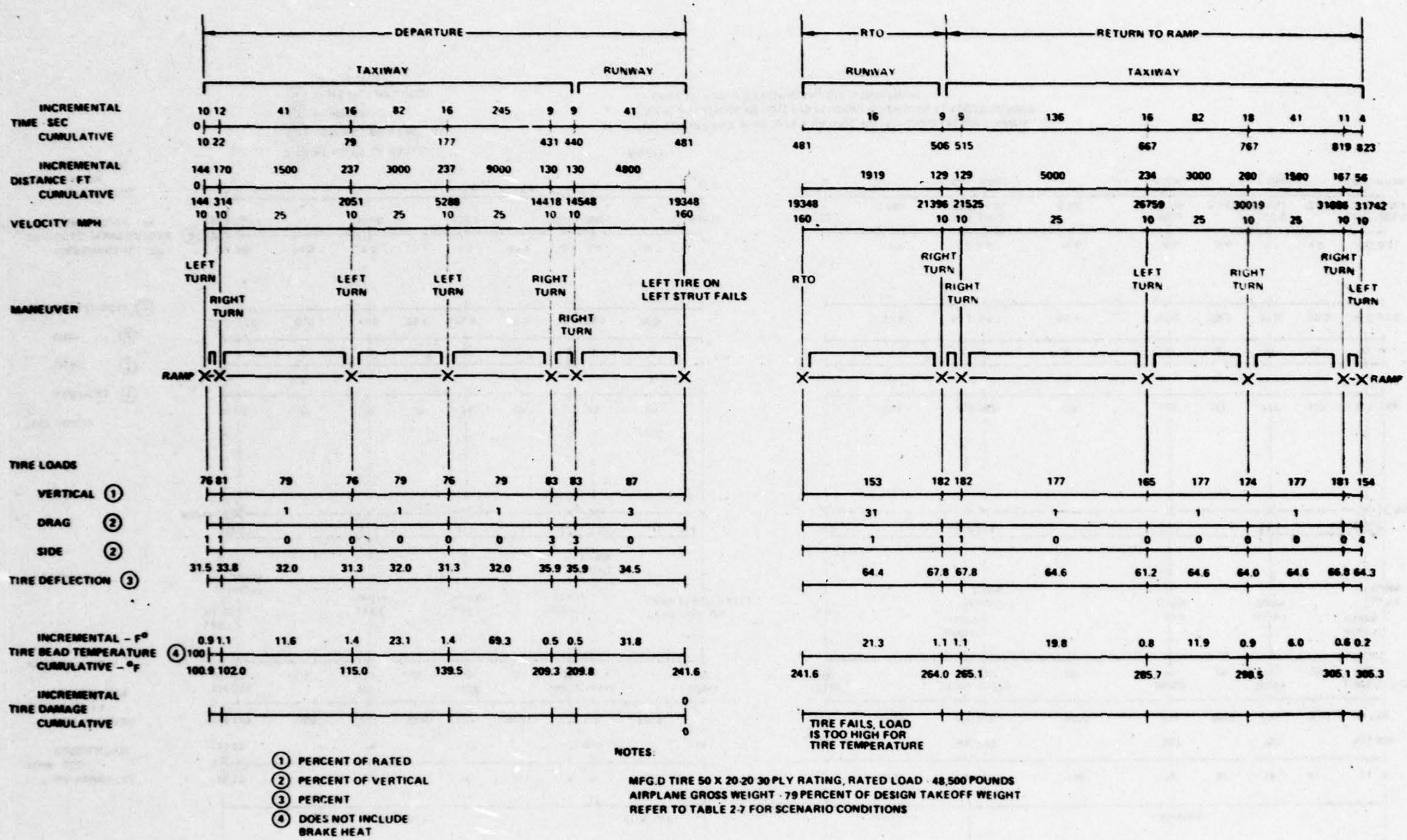


Figure 2-24. Takeoff Run Followed by RTO Scenario: Dual Gear, Typical Takeoff Gross Weight, Adjusted Pressure, Right Tire on Left Strut Fails During RTO

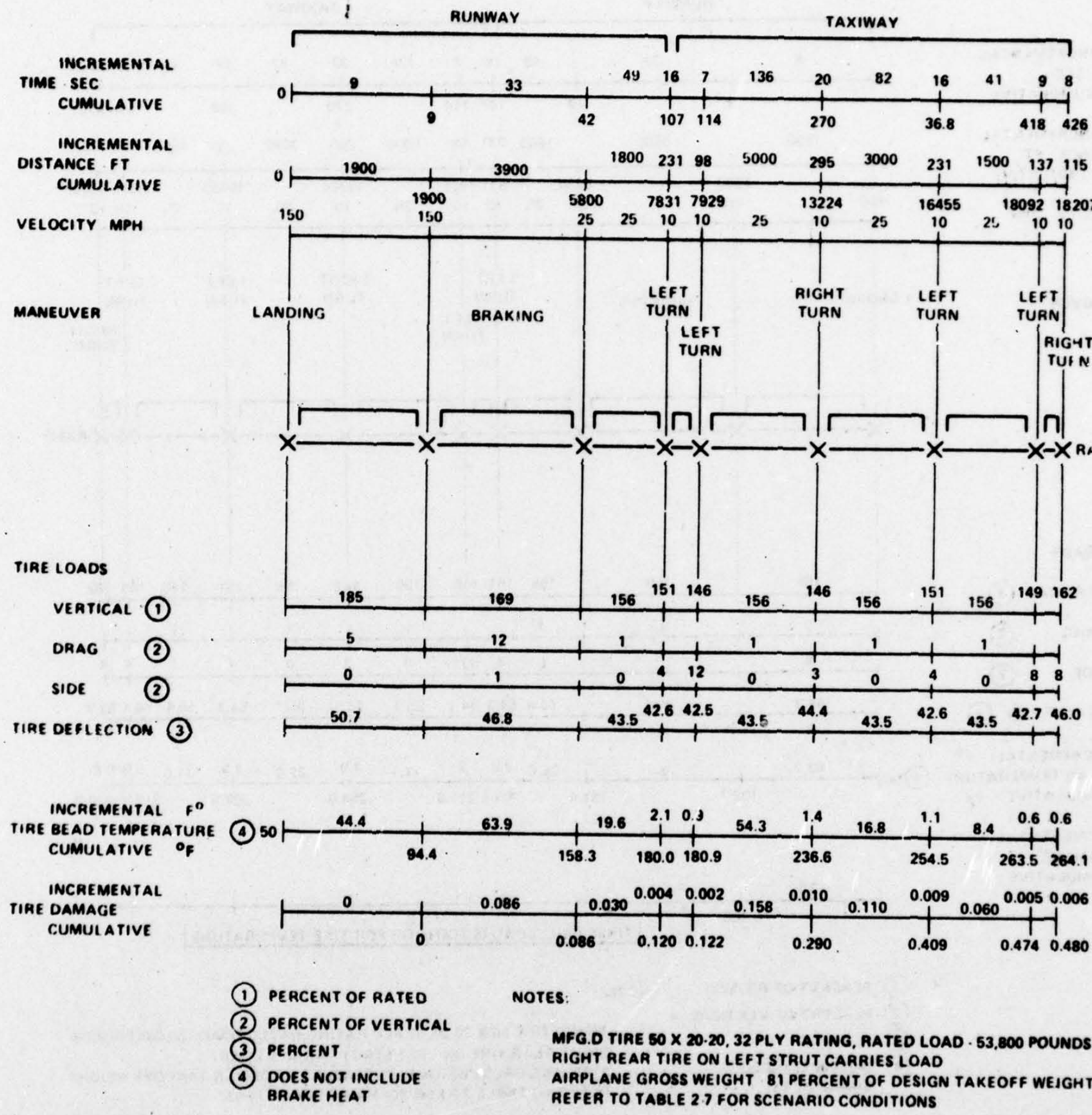


Figure 2-25. Landing Scenario: Left Rear Tire on Left Strut Failed at Touchdown, Dual-Tandem Gear, Moderately Heavy Gross Weight, Rated Pressure

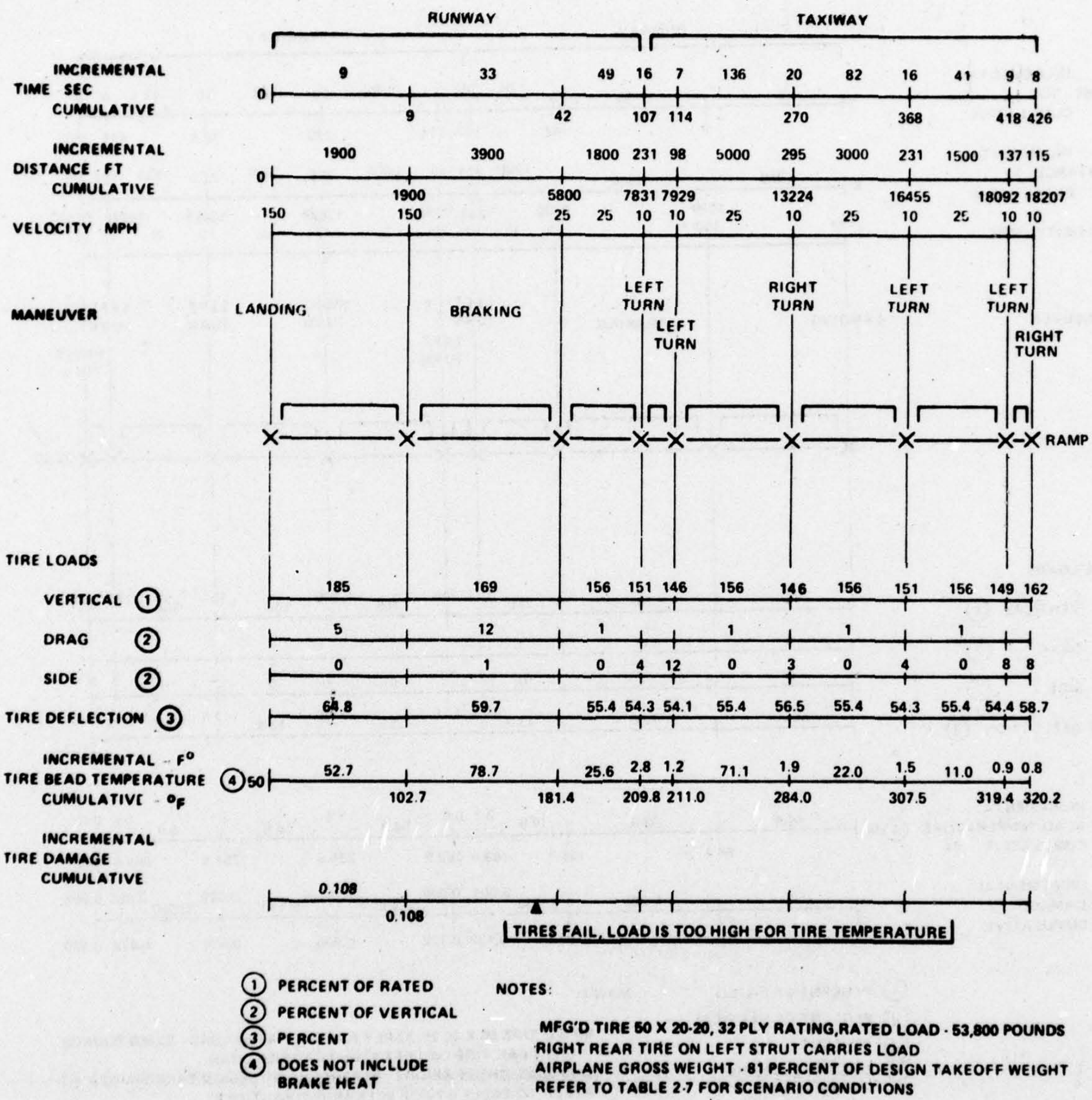


Figure 2-26. Landing Scenario: Left Rear Tire on Left Strut Failed at Touchdown, Dual-Tandem Gear, Moderately Heavy Gross Weight, Adjusted Pressure

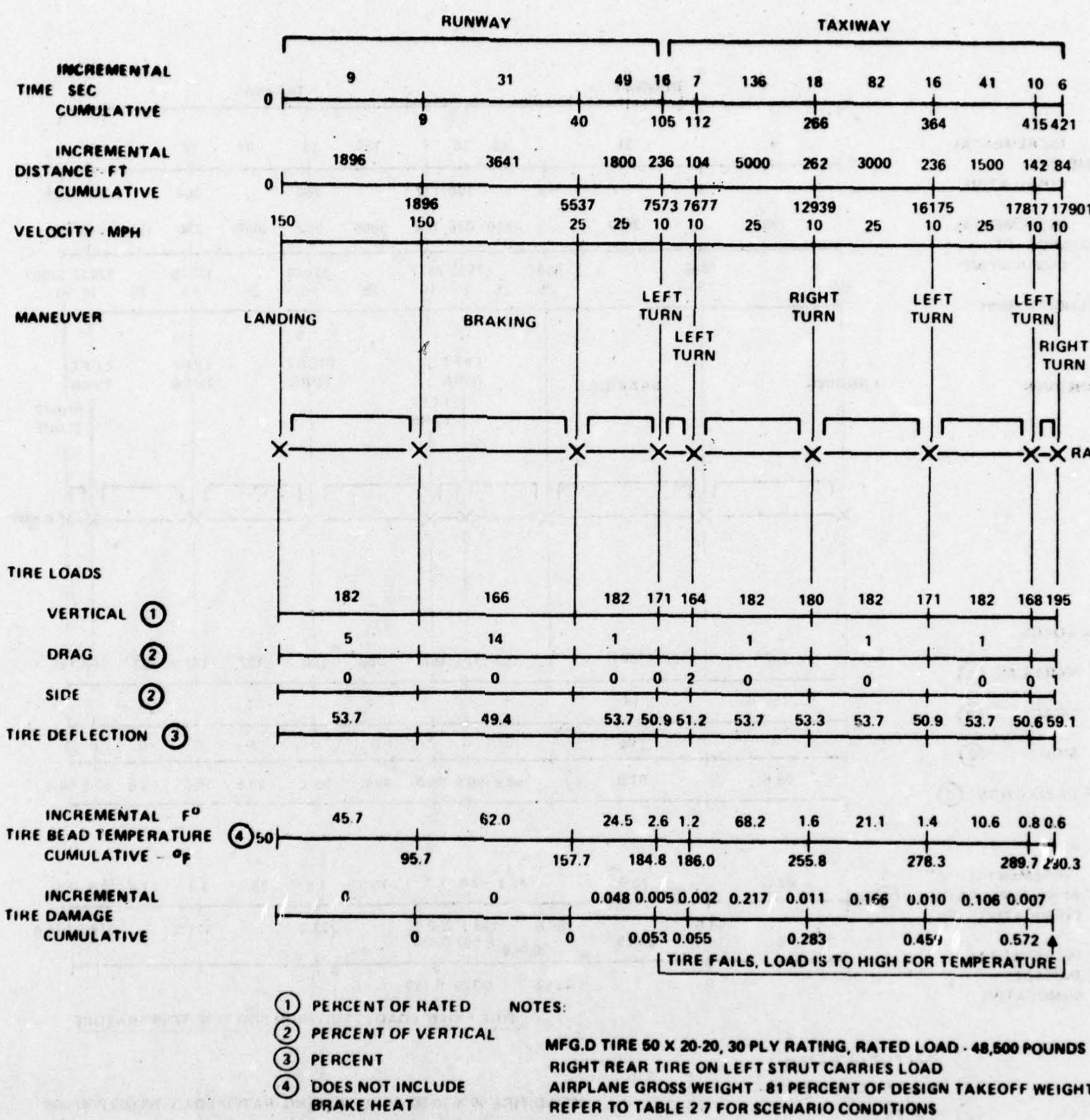


Figure 2-27. Landing Scenario: Left Tire on Left Strut Failed at Touchdown, Dual Gear, Moderately Heavy Gross Weight, Rated Pressure

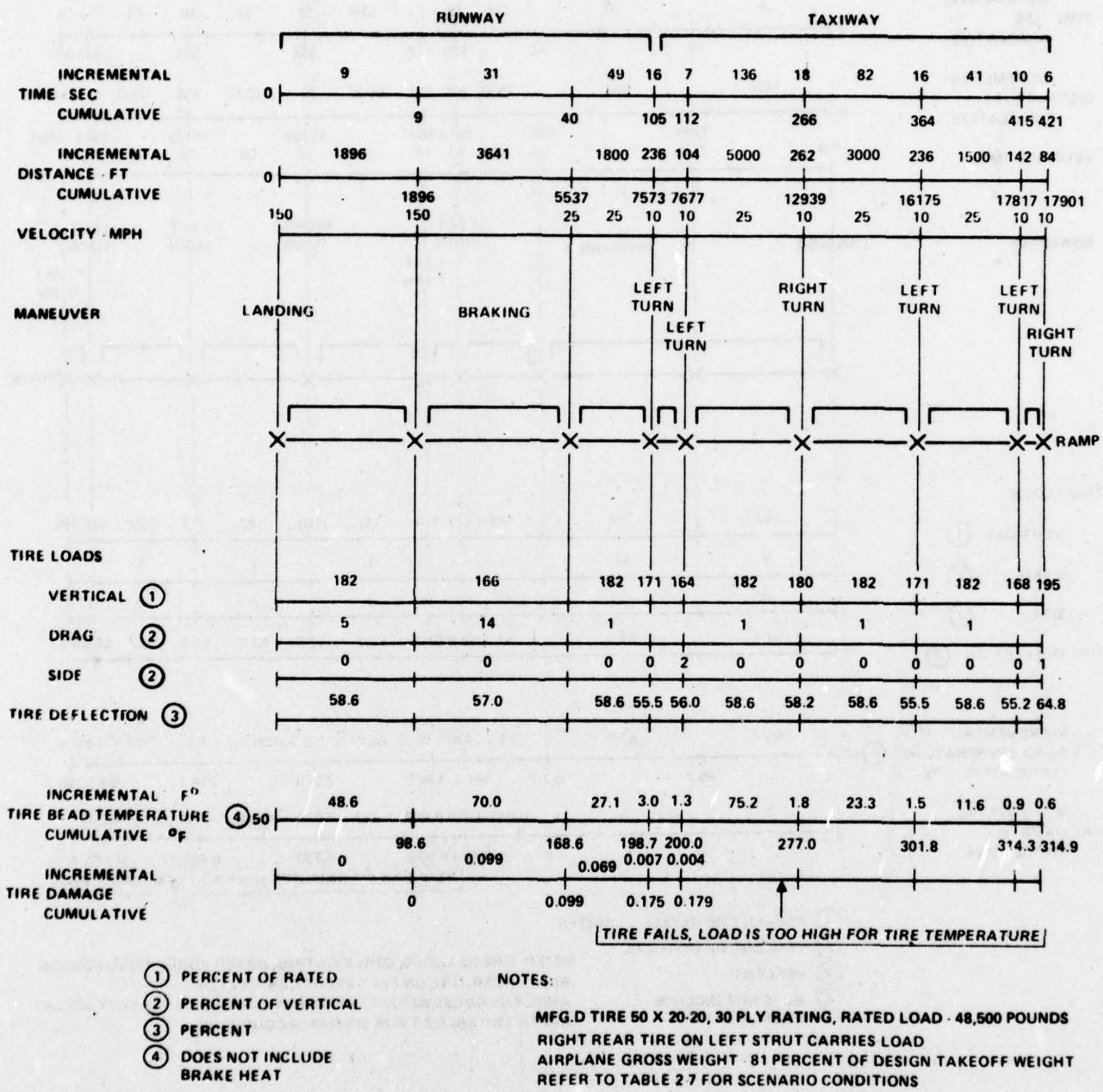


Figure 2-28. Landing Scenario: Left Tire on Left Strut Failed at Touchdown, Dual Gear, Moderately Heavy Gross Weight, Adjusted Pressure

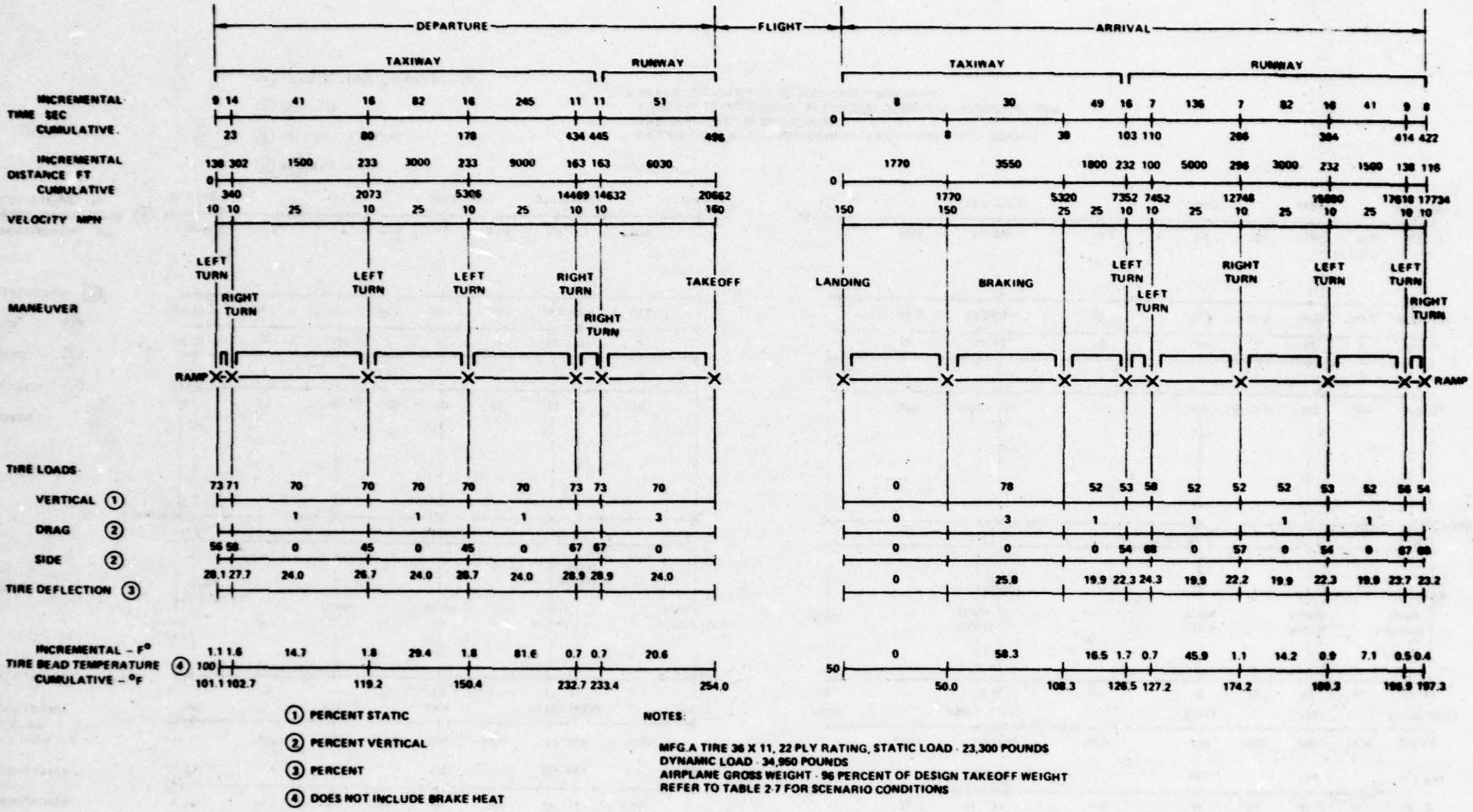
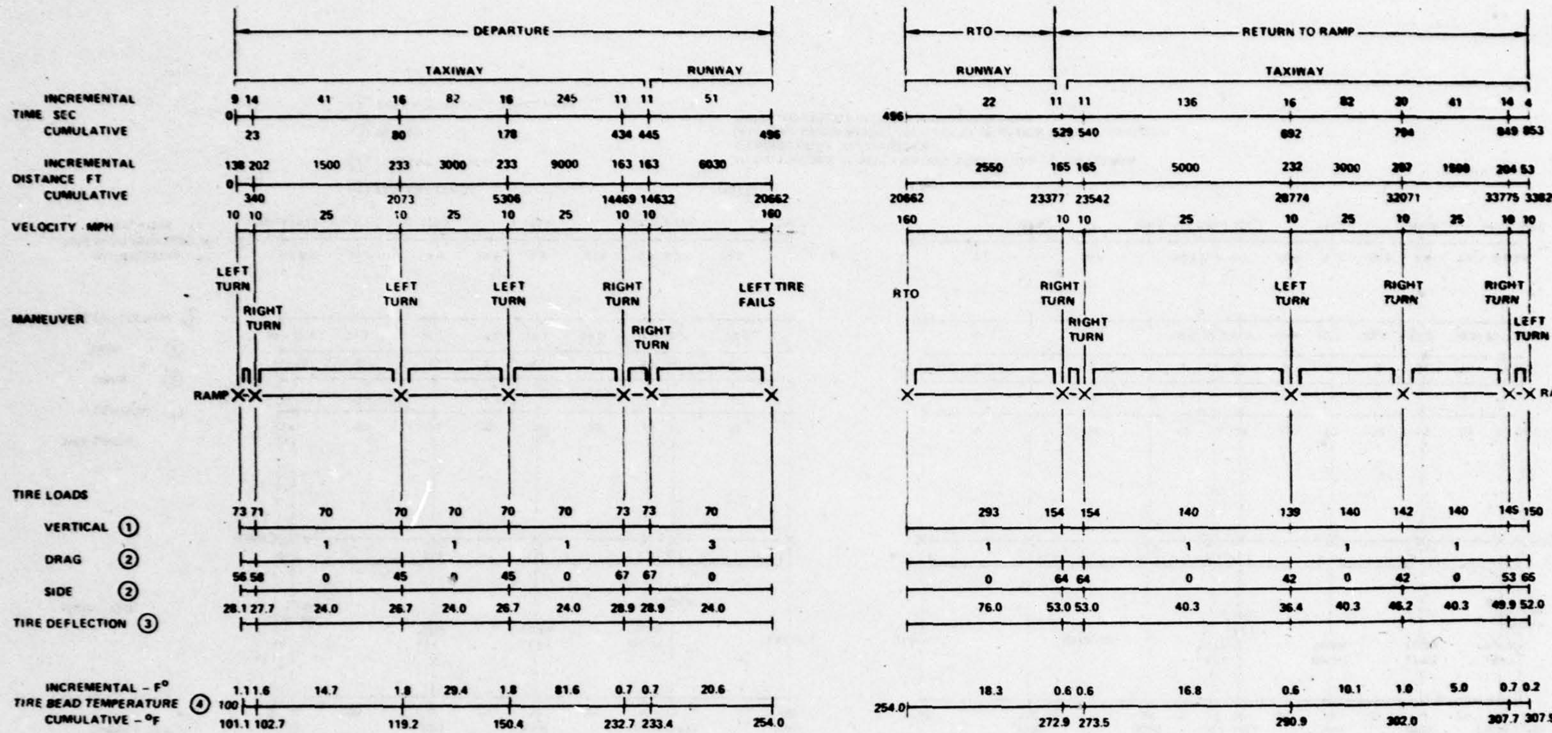


Figure 2-29. Takeoff and Landing Scenario, Nose Gear, Right Tire, Moderately Heavy Gross Weight, Rated Pressure



① PERCENT STATIC

② PERCENT VERTICAL

③ PERCENT

④ DOES NOT INCLUDE BRAKE HEAT

NOTES:

MFG A TIRE 36 X 11, 22 PLY RATING, STATIC LOAD - 23,300 POUNDS
DYNAMIC LOAD - 34,950 POUNDS
AIRPLANE GROSS WEIGHT - 96 PERCENT OF DESIGN TAKEOFF WEIGHT
REFER TO TABLE 2-7 FOR SCENARIO CONDITIONS

Figure 2-30. Takeoff Run Followed by RTO Scenario, Nose Gear, Right Tire Overloaded During RTO, Moderately Heavy Gross Weight, Rated Pressure

SECTION 3

INVESTIGATION OF TIRE IMPROVEMENTS FOR OVERLOAD CONDITIONS

3.1 GENERAL

Improvements to tires presently in service to obtain increased overload performance can range from an increase in pressure to a redesign requiring a new wheel. Since the design of a new wheel implies a substantial change in tire design, improvements of current tires are confined to those changes that will not alter the tire/wheel interface. The reasons for tire failure are examined and the information obtained is used to establish potential improvements for evaluation. The results of cost studies are presented to provide some indication of the economic impact of improving the overload capability of current tires.

Ideally, a tire with overload capability must be able to carry the overload for a certain distance with a start temperature commensurate with operations immediately prior to the onset of the overload and at any point in its service life. This definition requires that the following parameters be defined for a given tire application.

- Overload start temperature.
- Distance to be traveled in the overload condition.
- Wheel speed during the overload period.
- Magnitude of the overload.
- Number of flights that a tire carcass can be subjected to and still meet overload requirements.

The values that are assigned to these parameters depend upon the operational gross weight of the airplane in question which can vary depending

upon the utilization made by a particular airline. If long-range flights are contemplated, the takeoff weights will approach the maximum design takeoff weight. On the other hand, if numerous short range flights are made, the takeoff weight may be closer to the design landing weight. Thus, it is conceivable that the tire overload capability and life will be tied to the airplane and its use.

Although it is highly desirable to meet the ideals stipulated for an overload capable tire by providing improvements for current in-service tires, from the practical viewpoint, this goal most likely cannot be reached for airplanes operating near their maximum takeoff weights. One of the constraints is that certain changes may overburden the current wheels. Changes such as increased tire pressures may reduce rim life and tires capable of running hotter may reduce the strength of the wheel material. Another constraint may be that increasing the number of plies to provide greater strength will result in greater amount of material in the bead area which, in turn, may result in a faster temperature rise for a given distance traveled.

3.2 REASONS FOR TIRE FAILURES

A tire, like many other articles, is not a constant quantity, its performance reserve depends on age, loads, temperature and damage from foreign objects (FOD). The strength of a tire is on a declining scale throughout its service life. The effects of loads, temperature, and FOD can, to some extent, be limited by strict adherence to recommended loading and inflation practices in addition to sensible maintenance procedures. The effect of age is not considered to be significant within the service life of a tire based on today's technology and materials.

The foregoing statistical and analytical evaluation provide the following basic reasons for tire failure:

- **Overheat**
- **High stresses**
- **Combination of both**
- **Wheel rim failure**

Foreign objects are responsible for cuts and point impact damage. The frequency of these incidents is largely controlled by the housekeeping practices of all the airports.

3.2.1 Overheat

There are three major contributors to overheat: environmental heat, brake heat and tire self-generated heat. The environment in question consists of the pavement and ambient air. On a 110 degree Fahrenheit day the temperature of an asphalt pavement can exceed 180 degrees Fahrenheit. A tire at rest on the pavement will soak up this heat and exhibit a temperature gradient commensurate with the tire heat being absorbed by the surrounding air. Both the pavement and ambient air elevated temperatures hinder tire cooling after a flight and in this manner also contribute to high tire temperatures at the start of taxi which then influences the temperature reached by the tire during ground operations.

Brake heat is mostly radiated and its effect on tire temperature is located in the bead area. According to Figure 9 of Reference 3 it takes about 10 minutes after heavy braking for the tire bead to reach its maximum temperature. If continuous braking is limited only to RTO's and landings, peak tire temperatures from braking will, for most cases, occur at the ramp. Unfortunately, brake drag from malfunctioning brake systems will generate heat during taxi prior to takeoff and, if delays occur, can result in significant tire temperature increases such that the tire may fail during the takeoff run, especially if exposed to increased loads from runway crown effects.

For a given number of tire revolutions traveled self-generated heat is influenced by taxi speed and tire deflection. This relationship is depicted in Figure 3-1. The relationship indicates there is a substantial heat rise associated with high taxi velocities and tire overdeflection. For example, temperature rise could be reduced by over 40 Fahrenheit degrees by reducing taxi speed from 50 to 10 MPH. But, the taxi time for the same distance will be increased. For a 2¼ mile taxi distance the time will increase from under

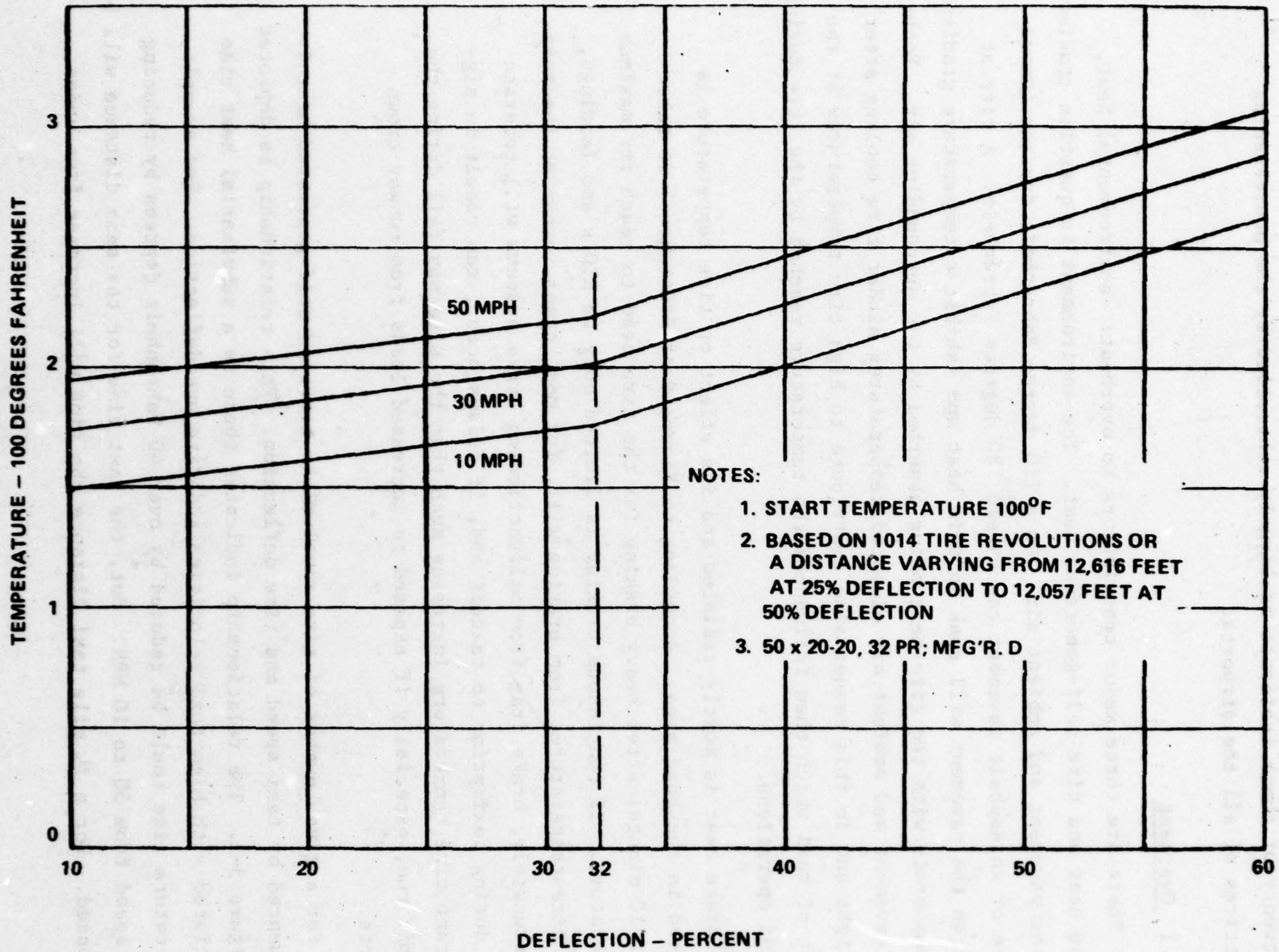


Figure 3-1. Relationship of Tire Bead Temperature, Deflection and Velocity

3 minutes to over 13 minutes. Since the tire temperature also increases with distance traveled, an unacceptable operational procedure emerges; that is, the further the taxi distance the slower the allowable taxi speed to reduce the chances of overheating the tire.

The problem is further compounded in that idle thrust of most modern jet transports exceeds that required to maintain taxi speed, necessitating braking. Thus, if a lower taxi speed is maintained, which requires a longer time for a given taxi distance, heat from the essential braking becomes a significant contributor to the temperature experienced by the tire.

3.2.2 High Stresses

High stresses, except for point impact, are caused by overdeflection, either as a result of underinflation or an overload. Underinflation results from poor maintenance practices or tire leaks. Most airlines have procedures for ensuring that the tire pressure is maintained properly. However, for wear considerations, some operators select the pressure of a cold tire on the basis of maintaining a 32 percent tire deflection. As can be noted in the scenarios (see Figures 2-14 and 2-20 for instance) the 32 percent deflection is exceeded during turns performed in taxiing to the runway and on the runway during takeoff. The increased deflection in turns is due to the vertical reaction of the gear to the centrifugal force of the airplane, the tilt of the strut loading the outside wheel of a dual or dual-tandem mount, and the tire sink resulting from the lateral force acting on the tire.

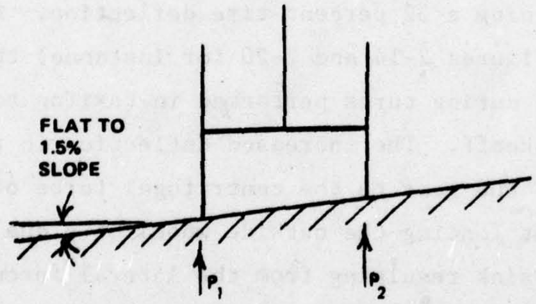
The greater than normal deflection experienced during takeoff is influenced by gear and airframe flexibility, gear camber, relative diameters and stiffnesses of tires on the same axle and the runway crown which is in the order of 1½ percent. By taking the most adverse tire configurations, such as wear, new tire diameter, tire stiffness and the runway crown, the difference in loads between the outboard and inboard wheels of a dual-tandem

gear can be as much as $\pm$ 20 percent of the mean vertical load. Table 3-1 compares tire loads for different combinations of worn/new tires. Except for the extreme case, it is not expected that tire damage will occur. In the extreme case damage will occur when the tire temperature exceeds about 290 degrees Fahrenheit. At that temperature the critical tire will roll about 14 miles before failure can be expected.

3.2.3 Combination of Both

Figures 3-2 through 3-4 illustrate the relationship of tire fatigue damage to distance traveled as a function of percent tire deflection for various values of taxi speed. The figures show the substantial effect that tire deflection has on tire life. By comparing the same deflections for each velocity it can be seen that very little damage is encountered

TABLE 3-1. EFFECT OF MOUNTING DIFFERENT TIRE COMBINATIONS ON THE SAME AXLE



TIRE CONDITION		MANUFACTURER		RUNWAY		LOADS-% RATED		DEFLECTION - %	
P1	P2	P1	P2	FLAT	CROWN	P1	P2	P1	P2
WORN ①	NEW	A	D		X	80	120	27.8	34.6
WORN	NEW	A	D	X		89	111	30.3	32.4
WORN	NEW	D	D		X	88	112	26.8	33.1
WORN	NEW	D	D	X		98	102	29.1	30.3
NEW	NEW	D	D		X	93	107	27.9	31.5
NEW	NEW	D	D	X		102	98	30.2	29.2

① *Tire is worn to wear marker*

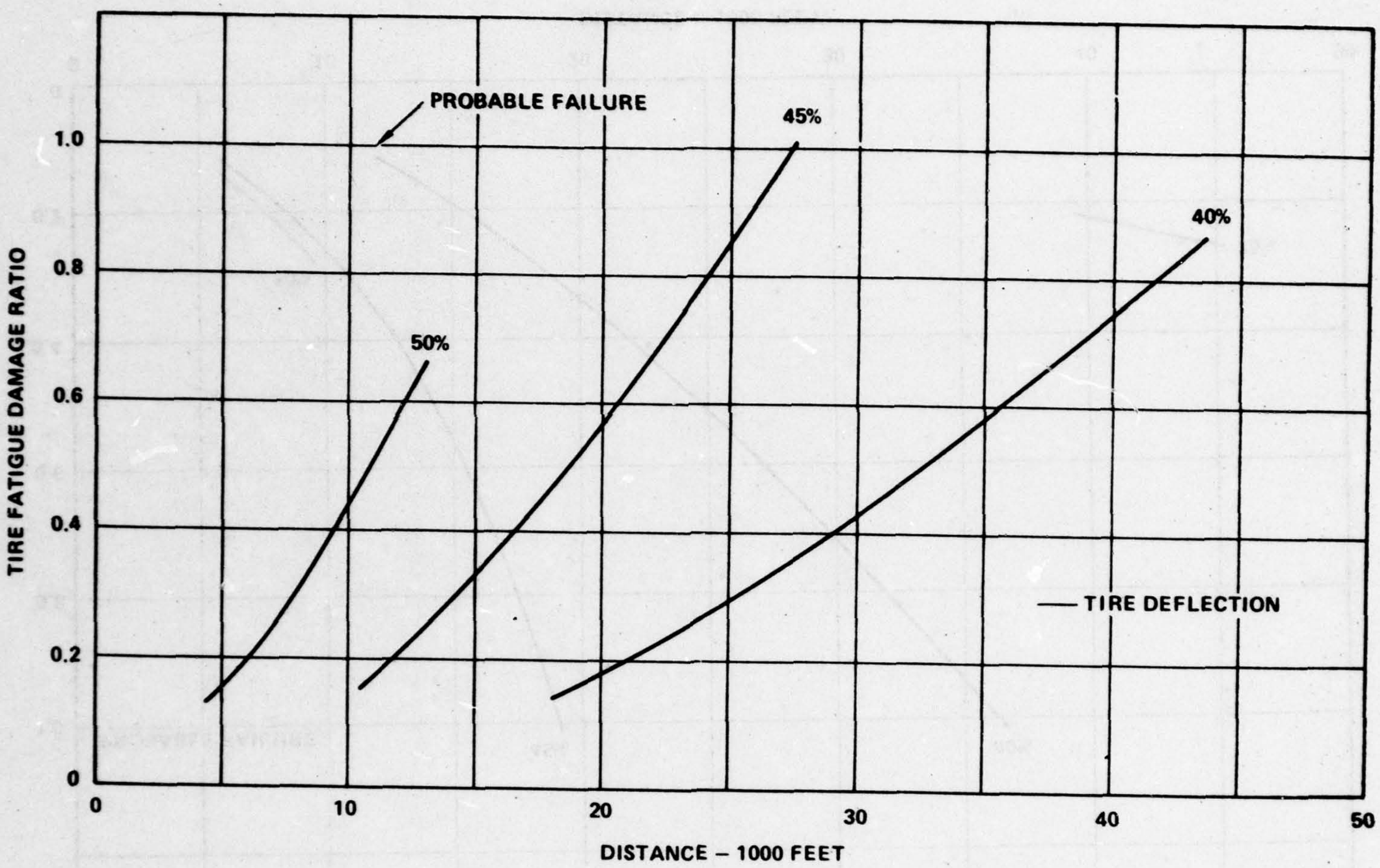


Figure 3-2. Tire Fatigue Damage, 10 Miles Per Hour

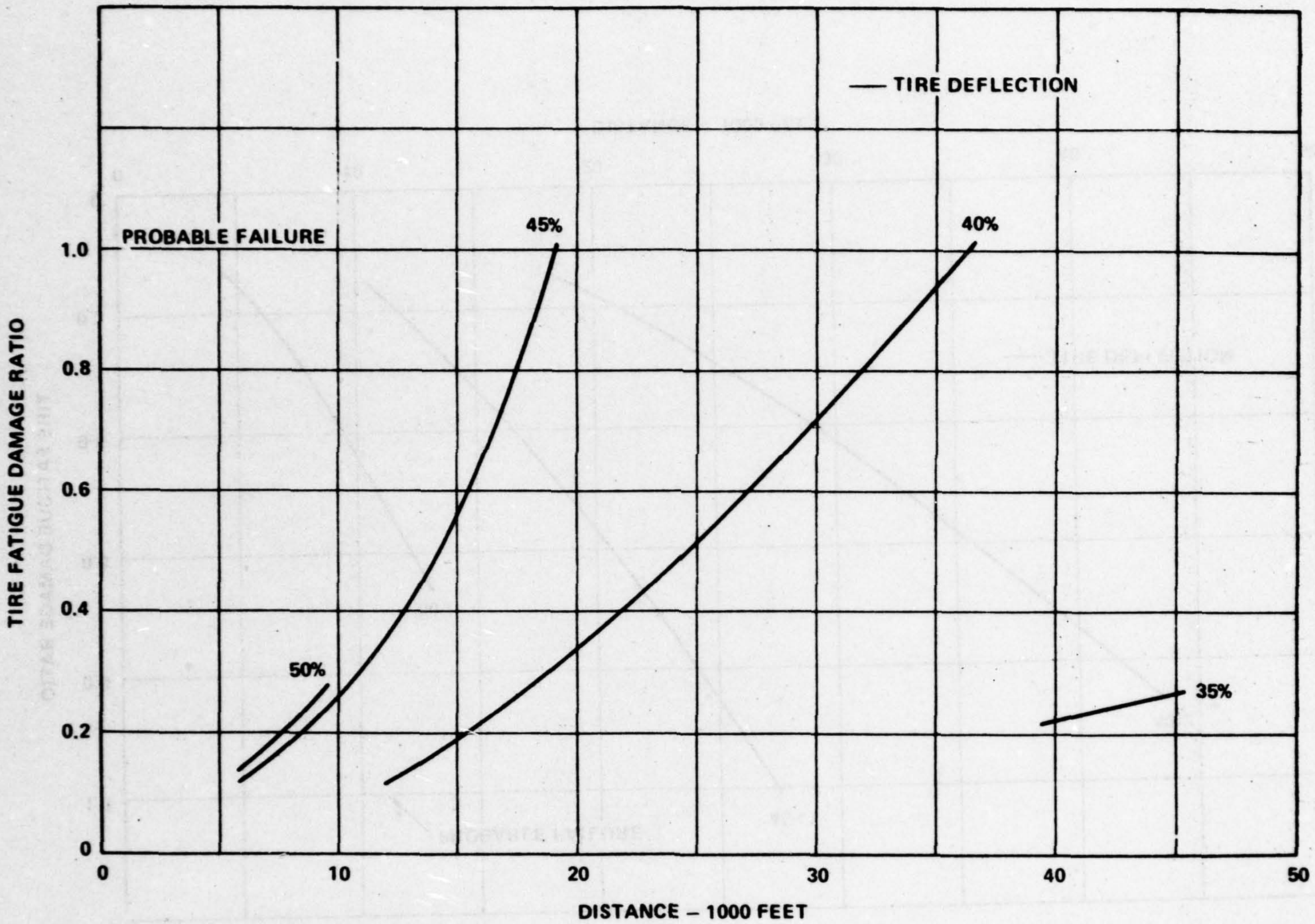


Figure 3-3. Tire Fatigue Damage, 30 Miles Per Hour

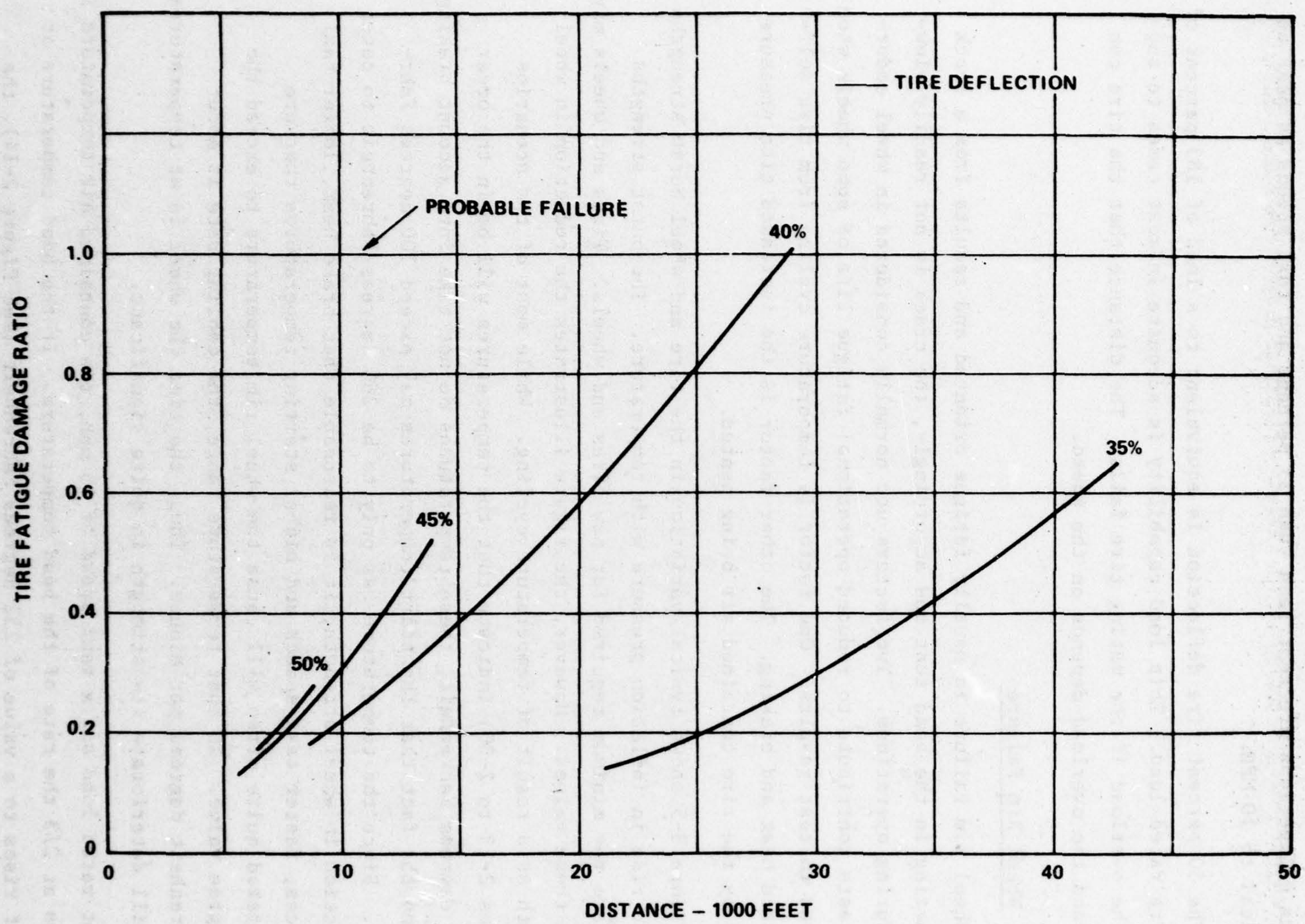


Figure 3-4. Tire Fatigue Damage, 50 Miles Per Hour

if tire deflections are kept less than 35 percent and taxi speeds as near as practical to 10 MPH.

The 50 percent tire deflection is equivalent to a load of 183 percent of the tire rated load. This load capability is adequate in most cases to support the overload if the mating tire fails. The distance that the tire can withstand the overload depends on the speed.

3.2.4 Wheel Rim Failure

Wheel rim failure is usually fatigue oriented and results from a crack originating in the bead seat and accordingly, the crack is not readily viewable during operations. Two factors not normally considered in wheel endurance tests contribute to reduced operational fatigue life of some wheels when compared to test results. One factor is temperature cycling from tire self-generated heat and braking. The other factor is the increased tire pressure caused by the tire contained air being heated.

Figure 3-5 shows typical variation in the tire and wheel burst strengths and the rise in inflation pressure with temperature. The burst strengths shown are the minimum required for new tires and wheels. Tires and wheels may exceed these values. However, the figure illustrates the reduction in wheel strength as a result of temperature cycling. While most of the scenarios (Figures 2-13 to 2-30) indicate that the temperatures will be in the order of 250 degrees Fahrenheit, these temperatures do not take into account braking heat and the fact that the start temperatures may exceed 100 degrees Fahrenheit. Since the temperature has only to be 260 degrees Fahrenheit to cause a reduction in wheel strength, it is reasonable that brake heat, longer taxi distances, faster taxi speeds and higher starting temperatures that are encountered quite often will cause the wheel rim temperature to exceed the 260 degree value. In that temperature range, the cooling rate is about 1½ Fahrenheit degrees per minute. Thus, the time the wheel is at temperatures that will deteriorate its strength is quite significant.

At rated load and a taxi speed of 25 mph, the contained air temperature increases at 2/3 the rate of the bead temperature. If the bead temperature at takeoff rises to a value of 252 degrees Fahrenheit (see Figure 2-14), the

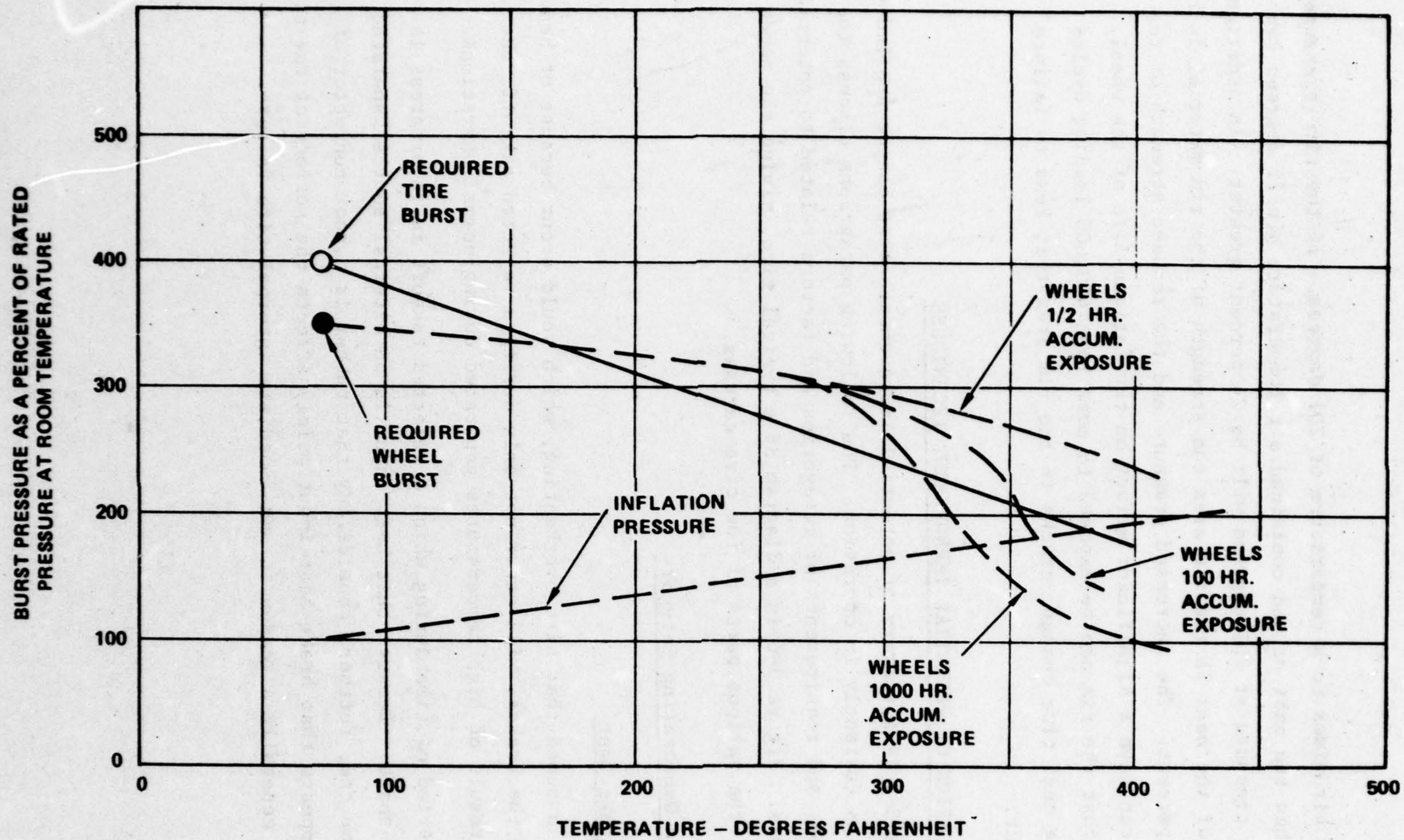


Figure 3-5. Tire and Wheel Strength Reduction with Temperature (Typical)

contained air rises to a temperature of 201 degrees. If the tire pressure is checked when the ambient and contained air temperature are 75 degrees Fahrenheit, the pressure at 201 degrees will be 24 percent greater. In addition, as a result of the heat in the rim area the strength of the rim material is reduced 15 percent. The increased pressure and the reduced strength of the material can have a significant effect on the fatigue life of the wheel. Considering that the rim can be exposed to more than 400,000 loading cycles before the next tire change, cracks in the rim area that lead to failure could occur.

3.3 EVALUATION OF POTENTIAL IMPROVEMENT TECHNIQUES

Table 3-2 is a summary of potential improvements that can be applied to tire designs currently in operation. The following paragraphs discuss the implications and requirements of categories and factors related to potential improvements. Figure 3-6 is a diagram of a typical tire, giving the nomenclature of the various parts of the tire carcass.

3.3.1 Tire Overheating Category

3.3.1.1 Brake Heat

It is assumed that tire overheating, which would occur because of heat input from the brakes, will occur not only during a rejected takeoff, but also as a result of high temperatures generated during normal operations.

The period of time during which a rejected takeoff is in progress is relatively short. Because that heat input is an external source generated for a short time and, further, considering that rubber is a poor conductor of heat, it appears that brake heat input mainly affects the surface of the tire and is not generally a reason for an immediate internal tire failure.

TABLE 3-2. TECHNIQUES FOR IMPROVING TIRE OVERLOAD CAPABILITY

Category	Problem Area	Potential Improvements
Overheat	Braking Heat	1. Tire materials having greater strength properties at elevated temperatures 2. Heat shielding to reduce amount of radiated heat reaching the tire.
	Tire Self-Generated Heat	1. Tire materials having greater strength properties at elevated temperatures. 2. Tire materials having less hysterises. 3. Tire constructions: a. Radial plys. b. Reduce number of plys by using stronger fabric reinforcement materials. c. Improved cross-sectional shape (reduce compression strains). 4. Reduce operating deflections by increasing tire pressure.
High Stresses and Fatigue Damage	Over Deflection	1. Reduce operating deflections by increasing tire pressure. 2. Alter tire cross-section shape to increase tolerance to deflection. 3. Use materials having greater elastic limits. 4. Use higher strength reinforcement materials. 5. Modify structural design to permit greater deflection prior to overstressing outer fibers.
Operational Damage	Cuts	1. Use compounds and/or reinforcement materials having greater cut resistance. 2. Improve tire tolerance to sharp objects on runway. 3. Define cut repair allowable limits etc.
	Point Impact Loads	1. Improve tread and/or carcass reinforcement to allow greater local tire compliance. 2. Allow tire to envelop objects by reducing (optimizing) tire pressure. 3. Develop improved report and removal procedure.

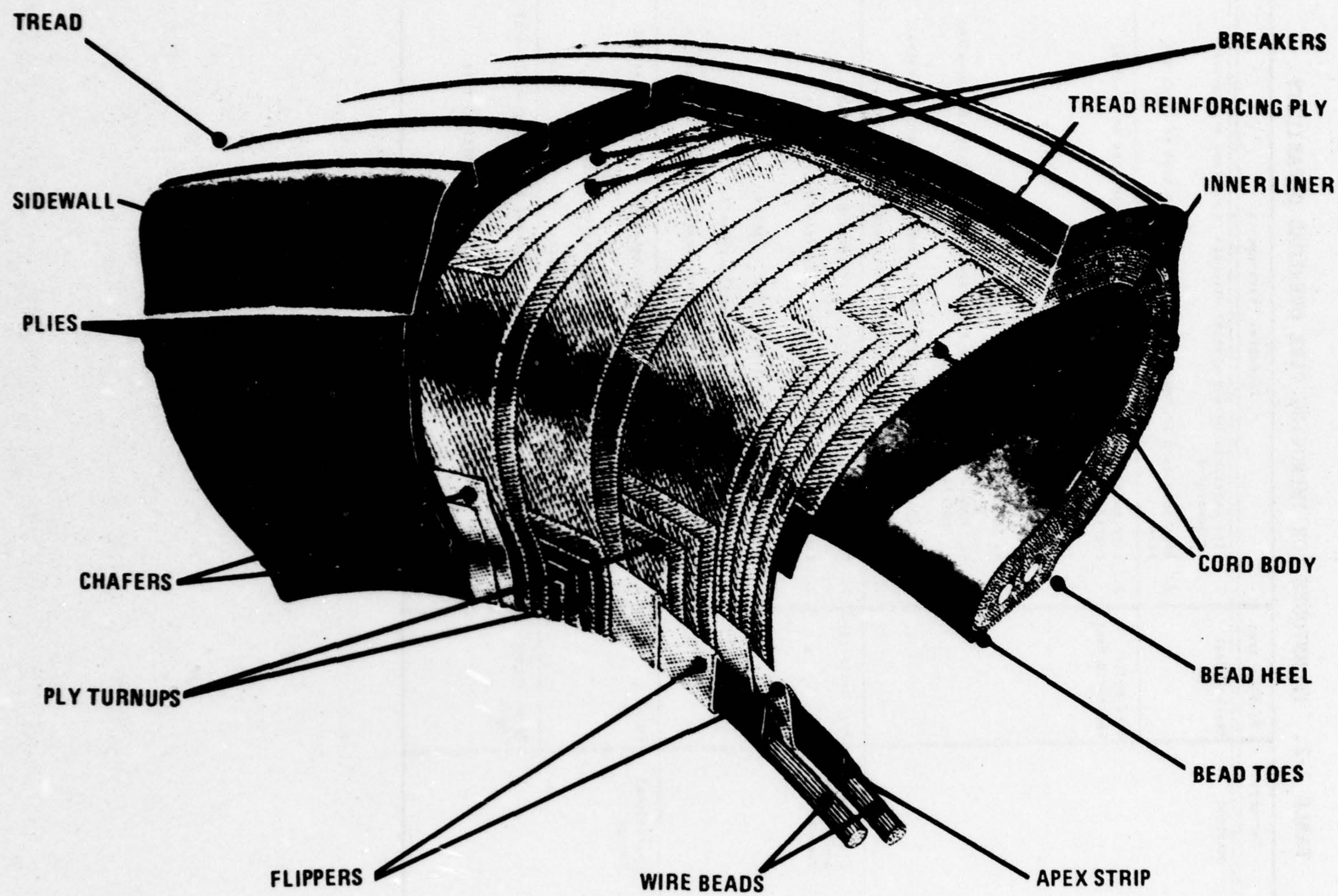


Figure 3-6. Diagram and Nomenclature for a Typical Tire

Any increase in ambient surrounding temperature is relatively detrimental to tire performance but is not in itself cause for a tire failure. However, even during normal operations, brake temperatures are frequently sufficiently high to cause eventual deterioration of rubber and nylon in the tire bead area. Any period of time during which the tire bead is subjected to temperatures in excess of 300 degrees Fahrenheit, a certain deterioration in tire reinforcement material strength occurs, which at some later time will be a contributing factor to bead failure. Interest in improving the tire's temperature environment, therefore, is not so much connected with an RTO operation as it is in ensuring that the tire during its normal service life will be protected from temperatures in excess of 300 degrees Fahrenheit. Therefore care should be employed in the design of the tire/wheel, brake assembly to ensure that the tire is protected from radiated heat.

With regard to improvements which can be made in the tire/bead area to assist in protecting the tire from elevated brake temperatures, the development of rubber compounds capable of withstanding higher levels of heat are discussed later in this section. In addition, tire reinforcement materials to be used in the chafer area, such as aramid fibers, fiberglass, steel, and various types of new nylons capable of withstanding higher temperatures than those nylons employed in the chafer area of the tire currently in production, are discussed later in this section.

Materials developed to improve the tire's ability to accept self-generated heat or those employed to reduce the self-generated heat will in great part have the side benefit of raising the tire's resistance to externally produced heat, such as that caused by high temperature braking. This study, while not ignoring heat input of the brakes, concentrates on the development of materials which will enable tires to perform satisfactorily at temperatures exceeding those considered safe and normal today. Therefore, if materials are developed which in themselves generate less heat, then the cumulative effect of outside heat together with self-generated heat will be lessened, thereby increasing the tire's ability to perform at elevated temperatures.

3.3.1.2 Tire Self-Generated Heat

Dynamic performance of a tire is related to the capacity of the system for storing and retaining energy while in a state of rapidly changing deformation. The ability to retain the dynamic performance is dependent on the heat generation within the system and its effect on the fatigue characteristics of the material. Compound requirements for maintaining tire integrity under severe overload conditions, therefore, involve the combined properties of high heat resistance (resistance to chemical breakdown, low hysteresis and excellent fatigue characteristics).

Potential improvements must be carried out concurrently in order to arrive at the optimum compound to be used in the carcass of the tire. Proper selection of the elastomer system, the vulcanization system and the antioxidant system is essential to maximum performance.

3.3.1.2.1 Tire Materials/Compounds

- Elastomer Systems

  While there are several heat resistant special purpose elastomers, such as silicone rubber, Viton, Teflon and the Phosphazine rubbers, none of these have the unique properties required for the aircraft tire performance. These elastomers have either poor tear resistance, high heat generation, low coefficient of friction, or poor fatigue life, or any combination of these shortcomings. In addition, they present fabrication, ply adhesion and tire integrity problems which have not been resolved.

  Therefore, the basic polymer systems are restricted to the general purpose elastomers; polyisoprene (natural and synthetic), polybutadiene and polybutadiene/styrene copolymer. These materials are selected since their physical and chemical properties are well-known; such as the rate of vulcanization, dynamic hysteresis, aging and low temperature properties. In addition, these polymers are compatible with themselves and are processable with present technology. These polymers are considered by themselves and in combination, as determined by

factorial designed experiments. Heat generation and fatigue characteristics are usually analyzed by Regression Analysis. The best combinations obtained from Regression Analysis are then used as the base polymer system for further studies.

- Vulcanization Systems

  Aside from the base polymer system, the vulcanization or cure system has the greatest influence on the heat resistance and hysteresis properties of a rubber composition. Numerous articles and texts are available describing cure systems for use in rubber products. To study the available acceleration systems alone requires many thousands of experiments and many hours of computer time. About 12 of the more promising accelerator combinations can be studied employing factorial experiments and regressing the heat generation and flex data. The primary or first data generated is resubjected to factorial experiments and again to Regression Analysis.

- Antioxidants

  Antioxidants are used primarily for protection of the rubber from oxygen attack. Since heat aging is in part an oxidative process, some heat resistance is contributed by these materials although their contribution is minimal when compared to the effects of the polymer system second vulcanization systems. In order to obtain the maximum benefits, the best known antioxidants described in the literature need to be studied by Factorial Design and the Flex and Heat Rise data regressed to give optimum level of antioxidant.

3.3.1.2.2 <u>Dynamic Test Methods - Tire Materials/Compounds</u>

<u>Heat Generation Tests</u> - The following types of testing methods are used to characterize the hysteresis and heat generation properties of the elastomer systems.

- Goodyear Vibrotester

  Involves force vibration of the test specimen under constant frequency, amplitude and temperature. Hysteresis as well as resilience and dynamic modulus data are generated. Temperature rise for constant force and amplitude modes is also determined and related back to relative tire performance.

- Goodrich Flexometer (ASTM 0623)

  Gives a measure of heat generation resulting from forced non-resonance vibration. Energy loss is measured directly as a temperature rise. Continuation of the test until blowout occurs gives an indication of relative tire durability under overload conditions.

- The MTS Tester

  The MTS tester also offers forced vibration testing similar to the Goodyear Vibrotester. This system permits testing under a wider range of frequencies, temperature, and load conditions.

Flex Fatigue Tests - Flex fatigue failures result from the gradual reduction of the material to withstand the stress or strain of service. Crack initiation and crack growth are both measurements of fatigue life.

- Test for Crack Initiation (ASTM D430)

  Method B - Uses a DeMattia flex machine to determine a relative crack initiation time and subsequent crack growth time resulting from flex extension or from a bending flex.

- Test for Crack Growth (ASTM D813)

  This test uses a pierced groove sample whereby the rate of growth of the initiated crack is measured during flexing.

Upon design and selection of the best overall system of polymers, antioxidants and curing ingredients for performance in these areas, further evaluations under conditions simulating the heat history experienced by the tire during service and retreading are needed. The evaluations should be made using several heat history levels since it is difficult to predict at which level tires experience overload. At the completion of these efforts, polymer ratios should be optimized along with the antioxidant and vulcanization systems. The results should be the basis for a compound design to incorporate into a tire designed for improved overload capability.

3.3.2 High Carcass Stress Category

3.3.2.1 Stresses During Operations at Rated Tire Deflection

In addition to incorporating materials into tires capable of sustaining elevated operating temperatures, much can be accomplished in the design and arrangement of the tire components to reduce the amount of flexing which occurs during service. In this manner the materials in the tire will be under less stress and strain and, therefore, the design of the tire can contribute considerably to improvement in performance under both normal and severe overload conditions. In view of the fact that the highest temperatures in an aircraft tire occur in the bead area, the study addresses itself to improving particularly that area of the tire so that less flexing occurs in this region.

The most common design aircraft tires in usage today have a reverse curvature to the individual plies as they enter the bead area of the tire from the sidewall area. When the tire is deflected under load, this area of the tire undergoes considerable distortion with many of the plies alternating between compression and tension. It is a generally accepted fact that if the materials in this area can be kept in tension only, then not only is the

temperature in that area reduced, but the mechanical stresses on the materials are also very much reduced. To accomplish this elimination of the compression-tension cycle, a new shape must be developed in the bead area such that when the tire is deflected, no compressive forces are present. By increasing the rim width to sidewall width ratio, the ply direction as it proceeds from the sidewall area into the bead area can be maintained in a convex line which will reduce the tendency for compression in that area. Figure 3-7 is a conventional bead shape in use today, and Figure 3-8 is a proposed configuration which will be referred to as a pseudo bead construction.

In the pseudo bead form, a false bead has been placed in what is normally described as the number three bead bundle location. No working plies are anchored to this bead bundle. The outermost ply actually at work in the tire is anchored to the middle or number two bead bundle. This change has the affect of operating a tire on a narrower rim while still maintaining the standard rims in use today. Compressive bead forces should be reduced and the ability to operate at brief overload deflections should result.

3.3.2.2 Stresses during Severe Overdeflection (Mate Tire Failure)

The pseudo bead construction described above may promote the usage of such materials as aramid fiber as a tire reinforcement because by eliminating the compressive forces in the bead area, materials which are excellent under tension, such as aramid, but poor under compressive forces can be utilized with attendant greater increase in strength values.

An additional benefit derived from these increased strength materials might be the reduction in the number of plies required to provide proper strength and thereby a reduction in tire thickness will be realized. By reducing tire thickness, the tire self-generated heat will be improved and the tire made more capable of maintaining its strength because of the lowered temperature. In addition to the aramid fiber there are increased denier

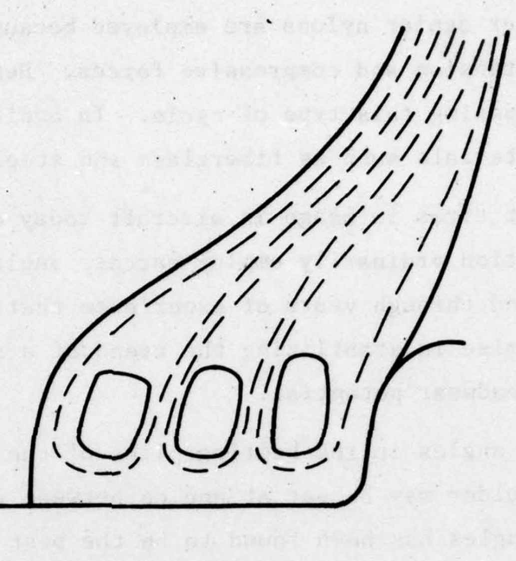


Figure 3-7. Conventional Aircraft Tire Construction

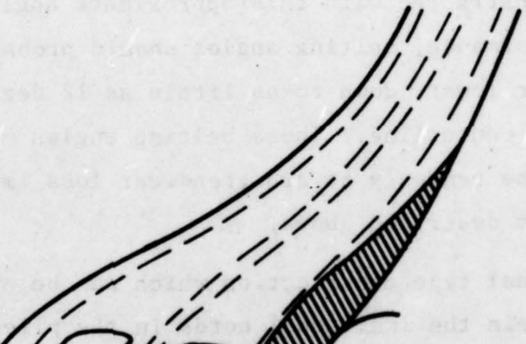


Figure 3-8. Proposed Pseudo Bead Aircraft Tire Construction for Bias or Bias Belted Tires Only

nylons available which may well be profitably utilized with the same benefits. Currently lighter denier nylons are employed because of the necessity to withstand both tension and compressive forces. Heavier denier fabric is very poor in accommodating this type of cycle. In addition to heavier denier nylon, other materials such as fiberglass and steel wire should be considered.

The current tires in usage in aircraft today of standard bias or bias-belted construction ordinarily employ carcass angles of approximately 34 degrees. It has been found through years of experience that this carcass angle provides the best compromise in stabilizing the tread of a tire and, therefore, enabling the greatest treadwear potential.

Currently, angles in the belting plies of the tire which run from shoulder to shoulder may be set at angles between 25 and 34 degrees. Again, this range of angles has been found to be the best angle approximation for providing a good solid tread foundation with attendant good treadwear. By raising the carcass angle up to as much as 70 degrees (when measured off of the circumferential centerline of the tire) the tire's ability to accept gross overdeflections imposed by high overloads may be greatly improved. If tires are constructed with this approximate angle for evaluation of over-deflection performance, belting angles should probably be continued at their current range or lower, down to as little as 12 degrees when measured off a circumferential centerline. These belting angles may have the effect of balancing out the tendency toward treadwear loss imposed by raising the carcass angle as described above.

An additional type construction which can be evaluated is that of the radial ply wherein the individual cords in the plies are run at 90 degrees from the tire centerline. This construction is in effect a further extension of the higher carcass angle designs. The radial tire is in general usage today in passenger, truck and earthmover type applications and has been proven successful in these usages. No reason is apparent why such a construction would not be practical in the sizes currently employed today on aircraft. In the previous discussion, the pseudo bead construction is to be of bias or bias-belted types. In the investigation of the radial ply design both standard construction and a pseudo bead variation should be evaluated to determine

what effect bead shape will have in the radial ply design in allowing over-deflection with no self-destructive tendencies.

3.3.3 Operational Foreign Object Damage

It is a statistical fact (see Table 1-2) that the largest number of tire removals occurring on commercial airplanes are caused by foreign object damage. Although this fact only indirectly involves the failure of a second tire (which is of greatest concern), nevertheless, if a reduction in foreign object damage failures to tires could be accomplished, exposure of other tires on the airplane to resultant overloads will be reduced. The known methods of reducing tread cutting and foreign object damage involve the use of tougher compounds which, unfortunately, also have a tendency to run a great deal hotter than is normally accepted in aircraft tires.

The use of increased carbon black will create somewhat of an improvement in cut resistance, but no great contribution to this feature will be made by compound changes. However, one possible approach to making an improvement in this regard involves the use of steel belting material in the tire. This change probably will be best accomplished in conjunction with a radial ply design. The steel belting will have the effect of protecting the carcass of the tire from the damaging effects of foreign objects encountered on aprons, taxiways and runways.

Standard ground vehicle highway tires such as truck and passenger currently have standards of plunger energy absorption which they must pass. These standards are a valuable criterion in the evaluation of tires as to their ability to withstand foreign object damage.

3.4 TRADE-OFF STUDIES - COST EFFECTIVENESS

In addition to th- technical aspects, the cost effectiveness of the tire improvements must be considered in determining the viability of potential tire improvements for meeting tire overload conditions. A comparison is made on an incremental cost per flight basis using (a) airplane repair cost attributed to tire failure, (b) changes in operating costs resulting from changes in weight and (c) tire costs attributed to tire improvements.

The development of an improved overload capable tire also improves the tire performance under normal operating conditions because the operational incidents requiring overload capability will be reduced. From paragraph 2.2.2, of the 207 cases of both single and multiple tire failures, 79 cases are multiple failures. (Not all cases of tire failure are recorded for the time period comprising the statistical sample, however, the sample is most likely sufficiently large to give trends.)

It is not expected that a 100 percent improvement can be achieved in an overload capable tire, especially from changes made to currently operational tires. However, if an improvement of 50 percent can be achieved in overload carrying capability of current tires, it is reasonable to assume that the incidence of single tire failure will be reduced by a similar percentage. Under these circumstances the incidence of overload failure will be reduced to 25 percent. For example, if 200 cases of tire failures occurred with unmodified tires and 80 cases resulted in second tire failure, a 50 percent improvement in overload capability could potentially reduce the total cases to 100. Of the 100 cases, considering the unmodified tire ratio of multiple tire failures cases to all failure cases, 40 cases will be overload. With the 50 percent improved overload capable current tire, the 40 overload cases could be potentially reduced to 20 cases or a 75 percent improvement.

As the percentage of improvement in overload capability from this program cannot be accurately predicted, a 50-percent improvement in overload capability is assumed for the trade-off study.

Data developed by Douglas Aircraft Company under FAA Contract, Reference 4, indicates that the following cost of repairs caused by tire failures per departure is encountered.

a. Airplanes equipped with dual wheel-configured landing gears; $0.25 per departure.

b. Large narrowbody airplanes equipped with dual-tandem wheel-configured landing gears; $0.57 per departure.

c. Widebody airplanes equipped with dual-tandem wheel-configured landing gears; $4.28 per departure.

The foregoing costs can be considered penalties which should not be exceeded on a cost effectiveness basis if no tire overload improvements are made. The cost penalties from potential loss of life and adverse publicity are difficult to determine and, hence, are neglected for conservativism in this study.

Assuming that 50 percent improvement is achieved, different values of the above repair costs are obtained. From Subsection 2.2 there are a total of 207 cases of tire failures of which 79 are overload failures. Using the previous logic, the 50 percent improvement will result in a reduction of failures to 103.5 cases of which 19.75 are overload failures after improvement. Considering that multiple tire failures will cause more damage than single tire failures, the estimated factor in savings for repair damage with tires having improved loadability that is applied to the previous cost of repairs is:

$$1 - \frac{103.5 + 19.75}{207 + 79} = 0.57$$

The savings in cost of repairs for airplanes equipped with the improved tires are:

a. Dual wheel; \$0.14 per departure

b. Narrowbody dual-tandem; \$0.32 per departure

c. Widebody dual-tandem; \$2.44 per departure

The cost of payload losses caused by greater tire overload capability is neglected because in only about 1 to 2 percent of typical modern transport airplane operations will it be required to reduce the payload as the result of adding a nominal amount of airframe weight. Accordingly, only the increased cost of operations is considered which is \$0.00685 per pound of added airframe weight per flight based on data for a typical widebodied transport.

Table 3-3 presents the estimated costs of improving the capability of current tires to withstand overload requirements. Tire weight, tire cost, and wheel weight changes are used in determining the cost of improved overload capability and are compared with repair costs per flight to determine the cost effectiveness of each improvement. The incremental tire weight change cost is obtained

TABLE 3-3. COSTS OF CURRENT TIRE OVERLOAD IMPROVEMENTS

(50 X 20-20 TIRE USED AS AN EXAMPLE)

Improvements	Incremental Tire Weight Change Cost Per Tire		Incremental Tire Costs Per Tire		Incremental Wheel Weight Change Cost per Wheel		Improvement Cost Per Flight Less Savings in Repair Costs Per Flight		
	Pounds	Cost Per Flight	Per Tire	Cost Per Flight	Pounds	Cost Per Flight	Dual	N/B[1] Dual-Tandem	W/B[1] Dual-Tandem
Increase Pressure 16 Percent to Provide Overload Protection(2)	0	0	$158.00	$0.158	8.7	0.0596	$0.73	$1.42	-$0.70
Pseudo Bead Construction	0	0	0	0	0	0	-$0.14	-$0.32	-$2.44
Stronger Reinforcement Material	-30	-$0.206	$ 84.75	$0.085		0	-$0.63	-$1.29	-$3.41
Higher Angle Carcass	30.5	$0.209	-$158.00	-$0.158	0	0	$0.06	$0.09	-$2.03
Radial Ply Construction	0	0	-$104.13	-$0.104	0	0	-$0.56	-$1.15	-$3.27

(1) N/B Narrowbody, W/B Widebody

(2) To Limit Maximum Tire Deflection to 45 Percent Under a 1.9 Times Rated Load Overload Condition.

by multiplying the estimated single tire incremental weight change by the cost of operations per pound of added weight per flight. Incremental tire costs are based on changes in the number of recaps ($158.00 per recap) from changes in tread wear and/or estimated increase in tire manufacturing costs. One thousand flights is assumed to be the life of each carcass. The use of high tire pressures requires additional strength in the rim area which results in additional weight being added to the wheel. This estimated weight is multiplied by the cost of operations to obtain cost per flight per tire.

The cost data for each of the factors pertaining to a particular improvement are summed algebraically and the repair costs per flight deducted. Negative results indicate a savings, while a positive value indicates a loss per flight as a result of the particular improvement.

The time span for making the overload improvements operational is of interest. Increased tire pressure is available immediately, and, except for operations in which runway flotation and/or fatigue loading of wheels and the airframe are a problem, the concept can be applied to all airplanes. The psuedo-bead concept is being evaluated presently and is further along in development than the remaining other concepts. From a purely cost standpoint, the stronger reinforcement materials appear to have the greatest potential. However, present day stronger reinforcement materials are unacceptable in compression for this application. Accordingly, the shape of the tires will require that fibers be in tension during normal operations including sideloads encountered during turns made with dual-tandem configured landing gears. Of the potential improvements, the radial ply construction and higher angle carcass will require new tooling and, hence, most likely will require the greatest lead time to develop.

SECTION 4

DESIGN CONCEPTS FOR NEW OVERLOAD CAPABLE TIRES

4.1 GENERAL

The design concepts investigated were not limited to in-service airplane tire/wheel/brake interface constraints. Thus emphasis was placed on tire shapes and wheel rim interface angles. When considering concepts for an improved overload capable tire, constraints such as runway flotation requirements and tire/rim interface problems have to be taken into account in addition to providing good tire wear characteristics. Basically, the concepts discussed emphasize reducing sidewall stresses, minimizing self-generated heat and/or increasing carcass strength. In addition to new tire overload concepts, runflat concepts are also discussed.

4.2 NEW TIRE CONCEPTS

Several approaches are presented in the way of new tire concepts to provide sufficient overload capability in a tire. These concepts include increased spring rate, radial ply construction, semiopen torus (SOT) design, and cooling techniques.

4.2.1 Increased Spring Rate

Potential for increasing overload capability is offered by increasing the slope of the load-deflection curve, since the temperature rise in a tire seems to vary approximately as the square of the deflection. A means of increasing the slope of the load deflection curve exists for present tires by effectively increasing the pressure buildup during deflection. This can be accomplished by decreasing the cavity volume of a tire with a filler. As an illustration of this method, a 50x20.0-20 tire with a rated load of 53,800 pounds at 190 psig inflation is used. The load-deflection curves show that at:

- 100 percent rated load the deflection is 30 percent at a 53,800 pound-load and an initial inflation pressure of 190 psi.
- 200 percent rated load the deflection is 45 percent at a 107,600 pound-load and an initial inflation pressure of 250 psi.

The 45 percent deflection is used because experience has indicated that up to 45 percent the tire can carry 200 percent rated load some reasonable distance during emergency operation. Preliminary calculations indicate that the insertion of a torus (33-inch OD with 20-inch ID and a section diameter of 9 inches) in the tire together with an initial tire inflation pressure of 215 psi will result in a load-carrying capability of 107,600 pounds with approximately 45 percent deflection. This size and shape filler will not receive any ground or runway loads during normal operation. The filler will have to be attached in some manner to the wheel. It can be made flexible and inflatable for ease in handling and installing, in which case it will need an extra or two-way valve. The inflation pressure of an inflatable torus will be approximately 300 psi to ensure adequate performance. The use of textiles in the filler would allow some diffusion so a periodic check of pressure will be necessary. If the filler is made of hard structure (aluminum, fiberglass, etc.) the pressure loss due to diffusion will be eliminated, resulting in less checking and maintenance efforts. A hard structure can still be inflatable and might be the lightest design. Depending upon the design chosen, this unit may be able to function as a runflat device.

4.2.2 Radial Tire Construction

The radial ply construction proposed under new tire concepts differs from that proposed for improved current tires in that the rim interface can be altered to optimize the tire for overload.

The more direct cord path of the radial tire as compared to the bias tire is subjected to less slippage of shear between plys and, hence produces less heat under deflection. This fact is readily shown in the following widely used expression:

$$\text{Interply Shear (psi)} = \mu_{\gamma} = \frac{2nt\text{Cos}\phi}{\rho\text{Sin}\alpha}$$

where, n = number of cords per inch

t = cord tension, pounds

ρ = radius of revolution, inches

α = cord angle from thread centerline

ϕ = angle between station tangent and vertical in tire cross section

AD-A064 979 LOCKHEED-CALIFORNIA CO BURBANK F/G 1/3
IMPROVEMENT OF OVERLOAD CAPABILITY OF AIR CARRIER AIRCRAFT TIRE--ETC(U)
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UNCLASSIFIED FAA-RD-78-133 NL

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The effect of cord angle is readily seen by the following grouping:

$$\mu_\varphi = \left(\frac{2nt\text{Cos}\phi}{\rho}\right) \frac{\text{Cos}\, a}{\text{Sin}\, a} \quad \text{or}$$

$$\left(\frac{2nt\text{Cos}}{\rho}\right) \frac{1}{\text{Tan}\, a}$$

A comparison of interply shear for different cord angles is shown in Table 4-1 (varying only a).

TABLE 4-1. INTERPLY SHEAR FOR DIFFERENT CORD ANGLES

Cord angle from tread center line,	tan a	$\frac{1}{\tan a}$	$\frac{\mu_\varphi}{\mu_\varphi(a=88^\circ)}$
88	28.6400	0.03492	1.00
85	11.4300	0.08749	2.50
75	3.7300	0.2679	7.68
60	1.7300	0.5773	16.54
45	1.0000	1.0000	28.65
30	0.5773	1.7320	49.63

Since the radial construction, α = 90 degrees, has theoretically a zero shear stress, for simplicity, α = 88 degrees is used as a reference. The rapid increase in interply shear with decrease in cord angle is readily apparent. One source of the heat involved in temperature buildup in tire is the shear phenomenon, hence, the interest in a radial tire. There are other advantages, such as more wear resistence, more uniform footprint pressure, and lower rolling resistence. If strain effects and hystersis are considered, a logical future design would be a flaxten radial construction.

The most suitable present fabric available is a 3-ply 333-denier flaxten cord with a nominal strength of 320 pounds per cord. If 15 ends per inch (epi) are assumed, this fabric will have a strength of 4,800 pounds per inch. If a 6-ply construction is assumed, the total carcass strength will be 28,800 pounds per inch compared to 25,000 pounds per inch for the present 50x20.0-20 34PR tire which has an 18 ply construction of nylon (840/2 with 33 epi.) Fewer plies, stiffer materials, and more direct or stable cord path all add up to a construction which is not only stronger but cooler running. Some areas of possible problems are cord lengths that are much more sensitive in a radial construction, heavy belt edges that tend to separate, and critical bead tie in. The cord lengths and the bead tie-in are interrelated and both contribute to the

uniformity of the ply load distribution. The weight of the radial ply construction is estimated to be approximately equal to that of a bias angle construction in the same size. Cost of the radial ply will average about thirty percent higher than a standard type because of the estimated increased number of individual components required in a radial. This cost should be offset to a certain degree by the estimated 50 percent longer wear inherent in radial belted tires.

4.2.3 Semiopen Torus (SOT) Tire

One of the most frequent causes of failure is lower sidewall compression. Sidewall compression can be reduced by narrowing the width between wheel rim flanges and reducing flange height to allow the tire to deflect a higher percent without developing areas of compression in the lower sidewall. Changing the flange angle such as in the category "B", "C" and "H" tires is a step toward improvement in this area. These tires are similar to the semiopen torus tire being developed for ground vehicles.

The SOT concept uses a narrow width between flanges and reduced flange height to allow the tire to deflect a greater percent without developing areas of compression in the lower sidewall. The areas of compression result from lower sidewall reverse curvature of conventional shaped tires. A potential improvement to the SOT concept involves eliminating the reflex contour in the lower sidewall altogether such as shown in Figure 4-1.

4.2.4 Cooling Techniques

Two basic approaches to the heat problem are:

- Minimize heat buildup by design. This approach involves concepts such as radial ply construction using materials with low hysteresis values.
- Redistribute the heat within a tire, i.e., using the cooler regions as sinks to cool the hotter regions.

The first approach is covered in previous discussions. A potential scheme for the latter approach involves increasing the thermal conductivity of the carcass by loading the rubber compounds with high thermal conductivity powders. The drawbacks to this concept are that tire weight may increase, adhesion problems may develop and the flexibility of the carcass may be

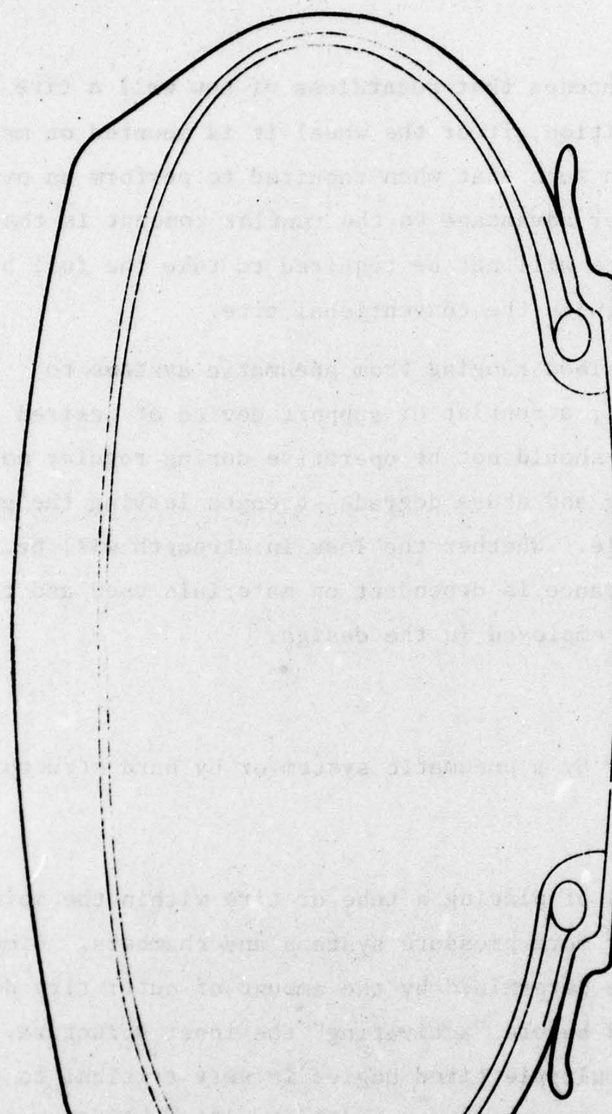

Figure 4-1. Semiopen Torus (SOT) Type Tire

reduced. Another potential scheme involves convective cooling by liquids in the air cavity or by forced circulation of the contained air.

4.3 RUNFLAT CONCEPTS

The runflat philosophy concedes that regardless of how well a tire is designed for the overload condition, it or the wheel it is mounted on may have been degraded in operation such that when required to perform an overload task it will fail. Another advantage to the runflat concept is that if a tire fails, the mating tire will not be required to take the full burden of the overload as is the case with the conventional tire.

Several concepts are described ranging from pneumatic systems to mechanical support. In general, a runflat or support device of desired or guaranteed overload capability should not be operative during regular normal service of a tire since flexing and abuse degrade strength leaving the emergency load capacity questionable. Whether the loss in strength will be significant under this circumstance is dependent on materials used and the degree of the margin of safety employed in the design.

4.3.1 Internal Support

Support is supplied either by a pneumatic system or by hard structure.

4.3.1.1 Pneumatic Support

Pneumatic support consists of placing a tube or tire within the main tire. The unit may have one or more pressure systems and chambers. Dimensions of this internal unit are determined by the amount of outer tire deflection which can be tolerated before "activating" the inner structure. Individual tire deflection on multiple tired bogies is very critical to the "paired" tire of a system. The constraints are (1) the allowable tire deflection to limit overloading of the "paired" tire to an acceptable degree (2) the internal unit is not so large as to be affected by tire deflections during normal service loading, and (3) the size (volume), pressure, and strength of the support unit must be consistent with the load requirements but still not overload the wheels. These three constraints are in mutual conflict. Some of the schemes contemplated will require stronger and larger wheels and some require two-way valves. Several of these systems are

adaptations of systems produced for the automotive market. With the exception of the foam-filled "lifeguard," these systems all require some maintenance or pressure monitoring and will probably add 50 to 80 pounds per tire for a 50 x 20.0-20 tire.

4.3.1.2 Mechanical Support

Mechanical support using a solid internal device is limited by items (1) and (2) in the foregoing paragraph. A consideration is that this unit, which can be clamped to the present wheel, can be damaged by heavy landing impact or hitting objects on the runway. This system will be maintenance free and, except for unusual operation, entirely passive (no loading until needed). Mounting this unit will be difficult. The expected weight per tire is approximately 80 pounds.

4.3.2 High Pressure Cellular Foam for Emergency Internal Support

This system is similar in some respects to the pneumatic systems discussed previously and will involve a small inner tire mounted inside the larger main tire. The design constraints are much the same as those earlier described, but this system will require no maintenance and is considered as "fail safe." The foam in the inner tire will have to be cured after the inner tire is mounted on the wheel. Inflation pressures up to 300 psi are considered feasible. Retreading will have to be done on the wheels. Added weight is expected to be 50 to 80 pounds per assembly.

4.3.3 Tire Runflat Capability

Tire runflat capability can be accomplished successfully for short distances using low profile tires of 60 to 70 percent aspect ratio which will provide minimal drop distance upon losing air. This system requires no internal or external devices, but will require wider wheels and wheel wells. These tires will be more difficult and expensive to manufacture. If a practical and effective means of anchoring the beads of present-day tires to the wheels can be found, this system might provide a simple interim solution.

The wheels will need some modification to minimize tire cutting and the lower sidewall area of the runflat-tolerant tire will require strengthening.

4.3.4 Mechanical External Stabilizers

This method will involve attaching either a skid or nonpneumatic rotating device to the brakes or wheels. Only in emergencies will it be deployed (actuated by pressure or deflection). These systems will be totally passive during normal operation and will require no changes to present tires. Wheel design changes may be required, depending on the method of attachment. The skid may have an ablative covering to adjust drag (high or low). Fewer units of this type will be required. They will probably be visible at all times for checking and will require no maintenance except after use. Weight, because less units are required, may be competitive with other devices. Landing gear redesign will be required, deployment can be fully passive; i.e., when the tires deflate, the bogie will settle on the skid or rotating device.

4.3.5 General

The development of internal and/or external support devices or the development of the ability of a deflated tire to support a high percentage of rated load for a takeoff and/or landing cycle appears to be eminently desirable. The principles described in the foregoing paragraphs all have attractive features and can most likely be designed to accomplish their purpose. Each, however, has significant disadvantages also, particularly in added weight, cost and greatly increased polar moments of inertia. Of the concepts listed, the mechanical internal support structure appears to offer the largest number of advantages, while exhibiting the fewest obstacles.

SECTION 5

OPERATING PROCEDURES INFLUENCING TIRE OVERLOAD PERFORMANCE

5.1 GENERAL

Operating procedures for improving the overload performance of tires fall in two categories: during normal operating conditions and during tire overload operating conditions following tire failure. The procedures discussed under normal operating conditions are concerned with avoiding undetected damage to tires in order to preserve their strength, as much as is practical, for an overload condition when needed. Operating procedures presented for a tire in the overload condition are concerned with minimizing further damage to the overloaded tire.

5.1.1 Operating Procedures Under Normal Conditions

Operating procedures under normal conditions include maintenance practices as well as pilot techniques.

The following practices may preserve the strength of the tires during normal operations.

a. Tire Temperature - As previously discussed, elevated temperatures can result in not only tire damage but also permanent loss in wheel strength, additional loads on the wheel rim from increased contained air pressure and faster than normal reduction in wheel rim fatigue life. The elevated temperatures are caused by the following factors:

- High initial tire temperature caused by (1) inadequate tire and brake cooling between flights, (2) high ambient air temperature, and (3) high pavement temperature (on a 110 degree Fahrenheit day the pavement temperature can exceed 180 degree Fahrenheit.) (Note: Forced cooling will reduce the initial temperature in all three cases. In locations where temperatures are in the order of 75 degrees Fahrenheit, it will take approximately

2 hours to cool the tires without the benefit of forced air circulation or cooling activity.)

A problem similar to the inadequate tire and brake cooling between flights is the case of the moderate RTO (resulting from other than tire problems) in which the cause of the RTO is remedied immediately and the airplane could be ready for another takeoff. However, the RTO has further increased the tire temperature and the tire will be exposed to additional heat input from the brakes and from the long taxi back to the takeoff position. The temperature increase can be as much as 100 Fahrenheit degrees. In addition, the takeoff run should add another 30 to 40 degrees, which, when considering the tire temperature reached prior to the RTO, may result in a tire temperature of well over 300 degrees Fahrenheit prior to being airborne. From Figure 3-5 most of the tire and wheel strength margin has been used at this temperature and as a result, multiple tire failures could occur during a subsequent RTO from a takeoff run.

Taxi velocity influences the rate at which heat is generated in the tire. For the same distance traveled and the same tire deflection, taxi velocities above 10 miles per hour may result in the following percent increase in tire bead temperature as compared to that of 10 miles per hour.

Velocity - Miles per Hour	Percent
20	21
30	31
40	45
50	58

When taxiing a long distance, the tendency is to increase the taxi speed. This action will have a very deleterious effect

on tire heat buildup because, not only is additional heat being generated by the extra distance traveled, but also the increased taxi speed is generating heat at a faster rate. However, if excessive braking has to be used to maintain a slow taxi speed, brake heat may detract from the benefits of the slow taxi speeds.

- The amount of tire deflection affects the self-generated heat rate. If airport pavement strength and airplane ground operations fatigue life permits, rated tire inflation pressure should be used instead of tire pressures adjusted to provide a 32 percent tire deflection at airplane operational gross weights.

  Inasmuch as the amount of tire deflection influences the rate at which heat is generated, the avoidance of mounting mismatched tires on the same axle will be beneficial in minimizing self-generated tire heat by preventing one tire from being deflected more than necessary (see Table 3-1.)

b. Tire Stresses - Since compression stresses in the lower sidewall influence the structural integrity of the tire, maintenance, and operational policies that help to minimize tire deflections and result in lower sidewall reverse curvature will be beneficial. The following factors should be considered for preserving the tire structural integrity:

- As in the case of minimizing tire heat buildup, the use of rated pressure in flights, where airplane fatigue life and runway strength permits, will minimize tire deflection. In addition, the overload capability will be at a maximum as compared to a practice which adjusts tire pressure to provide a deflection of 32 percent. However, the potential fatigue life of the wheel could be affected when operating the tire continually at rated pressure.

- Tire pressures should be checked at a time that will allow the tire heat from previous operations to dissipate the greatest amount. The tire temperatures at this time should have the least deviation from the original servicing conditions. (Note: The operating

manuals of transport airplanes contain information regarding the disposition of tires that are underinflated beyond certain limits and tires that are on the same axle.)

- The rear tires of airplanes equipped with dual-tandem configured main gears are exposed to high side loads. The severity of the side load is a function of the turn radius and the closeness of the tire to the center of the turn. Although the total deflection of the tire in a turn is increased in the order 2 to 3 percent (for example, 30 to 33 percent), the deflected shape of the tire sidewalls is not symmetrical. The sidewall towards the center of the turn will have an exaggerated double curvature in the lower sidewall, the severity being a function of the turn radius and the closeness of the tire to the center of the turn. Therefore, avoiding sharp turns, where practical, will help preserve the tire lower sidewall strength.
- As in the case of tire heating, the avoidance of tire mismatch on the same axle will minimize tire deflection to that which is necessary.

5.1.2 Operating Procedures Under Tire Overload

In the event that a mating tire of a failed tire is able to support the overload, the following procedures may be beneficial in prolonging the taxi life of the tire:

- Where practical, with airplanes equipped with dual-tandem configured landing gears, sharp turns, and turns with the overloaded tire on the side of airplane nearest the center of the turn should be avoided.
- Taxi speeds should not exceed 10 miles per hour.
- Braking should be avoided where safe to do so. If idle thrust is such that taxi speeds cannot be held to a low value,

consideration should be given to the shutting down of an engine rather than to apply brakes for taxi speed control.

- Where practical, minimize taxi distances. This procedure will minimize tire heat buildup and the number of cyclic loadings imposed on the overloaded tire.

SECTION 6

RESULTS AND CONCLUSIONS

6.1 RESULTS

- Based on the statistical data obtained in this program, 78 percent of the single tire failures and 62 percent of the multiple tire failures are associated with the takeoff-related stages of ground operations.
- Based on the statistical data obtained in this program, only 5 percent of the failures are nose gear tires of which 90 percent occurred during takeoff associated operations.
- Empirical equations for determining tire self-generated heat were developed and verified as part of the program.
- A method tor estimating tire fatigue damage has been developed. Some verification has been performed, however, additional verification using different size tires and operational tires having at least four retreads is required.
- Tire failure scenarios have been developed that present tire temperature, loads, distance traveled, time, and velocities for various typical ground operations including takeoffs, landings, and rejected takeoffs with tires at different pressures.
- Analysis shows that the four major causes of tire failure are overheat, overstress, combination of both, and wheel rim flange failure.
- Brake heat, although suspected of having a significant influence on tire temperature, could not be included in tire temperature predictions because of a lack of data.

- Increasing the pressure of current widebody tires to 116 percent of rated pressure will potentially improve overload capability and be cost effective (Refer to Table 3-3). This approach will reduce the fatigue life of wheels on some airplanes below acceptable limits and may not be acceptable for the pavement strengths of some airports.

6.2 CONCLUSIONS

- Normal ground operations, as described by the scenarios, do not produce combinations of self-generated tire temperatures and loads that will produce premature failure of current tires.
- The practice of using rated pressure for tire operations rather than adjusting the pressure to produce a deflection of 32 percent can enhance the overload capability of tires.
- There are potential cost effective modifications to current tires that may increase their overload capability.
- There are potential new tire designs that will provide total overload capability as well as increased performance under normal operations.
- Modified maintenance and operational practices can prolong the structural strength life of tires for normal and overload operations.

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APPENDIX

SR-52 CALCULATOR PROGRAMS

TABLE OF CONTENTS

TIRE DEFLECTIONS

(Pages A-2 Through A-4)

SAMPLE PROBLEM

Input

Fz = 53,800 Pounds	A
F_y = 18,000 Pounds	B
P = 190 PSI	C
F_x = 16,000 Pounds	D
P_R = 190 PSI	2nd A'
w = 19.13 Inches	2nd B'
S_{100} = 12.639 Inches	2nd C'
R = 0.0000576934 Inches per Pound	2nd D'
d_o= 49.3 Inches	2nd E'
S_o = 0.65 Inches	STO 10

Answer

% S_{zt} = 32.496 Percent	E

SR-52 User Instructions

TITLE TIRE DEFLECTIONS PAGE 1 OF 3

		◄A◄		
Vert. Load	Lat. Load	Tire Press.	Drag Load	Deflection
Rated Press.	Width	δ_{100}	R	Dia.

		◄B◄		

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter Program A		CLR	2nd	read	0
2	Enter Program B		2nd	read		0
3	Enter Vertical Load, F_z		A			
4	Enter Lateral Load, F_y		B			
5	Enter Tire Press, P		C			
6	Enter Drag Load, F_x		D			
7	Enter Rated Press., P_R		2nd	A'		
8	Enter Tire Width, w		2nd	B'		
9	Enter Deflec. at 100%, δ_{100}		2nd	C'		
10	Enter Deflec./Load Slope, R		2nd	D'		
11	Enter Tire Diameter, d_o		2nd	E'		
12	Enter Deflection 0 Load, δ_o		STO	1	0	
13	Calculate % Deflection, δ_{zt}		E			δ_{zt} %

Part No. 1220479

TITLE TIRE DEFLECTIONS PAGE 2 OF 3

PROGRAMMER P.C. Durup DATE 9 Aug 1978

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	46	2nd LBL			42	STO			03	3		A F_z
	11	A			00	0			85	+		B F_y
	42	STO		040 152	07	7			93	.		C P
	00	0			81	HLT			02	2		D F_x
	01	1			46	2nd LBL		080 192	04	4		E % δ_{zt}
005 117	81	HLT			14	D			65	X		A' P_R
	46	2nd LBL			42	STO			43	RCL		B' w
	12	B		045 157	00	0			00	0		C' δ_{100}
	42	STO			06	6			04	4		D' R
	00	0			81	HLT		085 197	54	)		E' d_o
010 122	02	2			46	2nd LBL			55	÷		REGISTERS
	81	HLT			10	2nd E'			53	(		00
	46	2nd LBL		050 162	42	STO			43	RCL		01 F_z
	13	C			00	0			00	0		02 F_y
	42	STO			09	9		090 202	05	5		03 P
015 127	00	0			81	HLT			75	−		04 P_R
	03	3			46	2nd LBL			93	.		05 w
	81	HLT		055 167	32	SIN			07	7		06 F_x
	46	2nd LBL			42	STO			65	X		07 R
	16	2nd A'			01	1		095 207	53	(		08 δ_{100}
020 132	42	STO			00	0			43	RCL		09 d_o
	00	0			46	2nd LBL			01	1		10 δ_o
	04	4		060 172	15	E			00	0		11
	81	HLT			07	7			85	+		12
	46	2nd LBL			93	.		100 212	43	RCL		13
025 137	17	2nd B'			05	5			00	0		14
	42	STO			65	X			07	7		15
	00	0		065 177	43	RCL			65	X		16
	05	5			00	0			43	RCL		17
	81	HLT			02	2		105 217	00	0		18
030 142	46	2nd LBL			55	÷			01	1		19
	18	2nd C'			43	RCL			54	)		FLAGS
	42	STO		070 182	00	0			54	)		0
	00	0			08	8			85	+		1
	08	8			55	÷		110 222	53	(		2
035 147	81	HLT			53	(			43	RCL		3
	46	2nd LBL			43	RCL						4
	19	2nd D'		075 187	00	0						

TITLE TIRE DEFLECTION PAGE 3 OF 3

PROGRAMMER P.C. Durup DATE 9 Aug 1978

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	01	1			85	+						A
	00	0		040 152	04	4						B
	85	+			65	X						C
	43	RCL			43	RCL						D
	00	0			00	0		080 192				E
005 117	07	7			04	4						A'
	65	X		045 157	54	)						B'
	43	RCL			55	÷						C'
	00	0			53	(						D'
	01	1			43	RCL		085 197				E'
010 122	54	)			00	0						REGISTERS
	65	X		050 162	09	9						00
	01	1			40	$2^{nd}x^2$						01
	00	0			65	X						02
	00	0			53	(		090 202				03
015 127	55	÷			43	RCL						04
	43	RCL		055 167	01	1						05
	00	0			00	0						06
	08	8			85	+						07
	85	+			43	RCL		095 207				08
020 132	01	1			00	0						09
	06	6		060 172	07	7						10
	93	.			65	X						11
	06	6			43	RCL						12
	07	7			00	0		100 212				13
025 137	65	X			01	1						14
	43	RCL		065 177	54	)						15
	00	0			54	)						16
	06	6			35	$\sqrt[x]{Y}$						17
	55	÷			03	3		105 217				18
030 142	43	RCL			95	=						19
	00	0		070 182	81	HLT						FLAGS
	08	8										0
	55	÷										1
	53	(						110 222				2
035 147	43	RCL										3
	00	0										4
	03	3		075 187								

TIRE TEMPERATURE RISE

(Pages A-6 Through A-12)

ΔTEMPERATURE RISE, TIRE BEAD

SAMPLE PROGRAM

V = 25 MPH, δ_{zt} - 27.8 Percent, Distance Traveled 14,110 Feet

Input for Cummulative $\leq$1014	Key
V = 25 MPH	A
δ_{zt} = 27.8 Percent	B
$N_{R_{s/t}}$ = 1014.0 Revolutions	C
Answer	
ΔT - 90.9 Fahrenheit degrees	E

Input for cummulative 1014 < $N_{R_{s/t}}$ $\leq$1821	Key
V = 25 MPH	A
δ_{zt} = 27.8 Percent	B
$N_{R_{s/t}}$ = 133.8 Revolutions	C
Answer	
ΔT = 6.2 Fahrenheit degrees	E

Total ΔT = 90.9 + 6.2 = 97.1 Fahrenheit degrees

SR-52
User Instructions

TITLE Δ TEMPERATURE RISE TIRE BEAD PAGE 1 OF 7

◄A◄

V	δ_{zt}	$N_{RS/T}$		ΔT

◄B◄

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
	Cummulative $N_{R_{s/t}} \leq 1014$					
1	Enter Program A		CLR	2nd	read	
2	Enter Program B		2nd	read		
3	Enter Velocity, V		A			
4	Enter % Deflection, δ_{zt}		B			
5	Enter Revolutions, $N_{R_{s/t}}$		C			
6	Calculate ΔTemp. Rise, ΔT		E			
	Cummulative $1014 < N_{R_{s/t}} \leq 1821$					
1	Enter Program A		CLR	2nd	read	
2	Enter Program B		2nd	read		
3	Enter Velocity, V		A			
4	Enter % Deflection, δ_{zt}		B			
5	Enter Revolutions, $N_{R_{s/t}}$		C			
6	Calculate ΔTemp. Rise, ΔT		E			
	Cummulative $N_{R_{s/t}} > 1821$					
1	Enter Program A		CLR	2nd	read	
2	Enter Program B		2nd	read		
3	Enter Velocity, V		A			
4	Enter % Deflection, δ_{zt}		B			
5	Enter Revolutions, $N_{R_{s/t}}$		C			
6	Calculate ΔTemp. Rise, ΔT		E			

Part No. 1220479

(Cumulative $N_{R s/t}$ ≐1014)

TITLE ΔTEMPERATURE RISE TIRE BEAD PAGE 2 OF 7

PROGRAMMER PC Durup DATE 4/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS
000 / 112	46	2nd LBL	
	11	A	
	42	STO	
	00	0	
	01	1	
005 / 117	81	HLT	
	46	2nd LBL	
	12	B	
	42	STO	
	00	0	
010 / 122	02	2	
	81	HLT	
	46	2nd LBL	
	13	C	
	42	STO	
015 / 127	00	0	
	03	3	
	81	HLT	
	46	2nd LBL	
	16	A'	
020 / 132	53	(	
	93	.	
	00	0	
	01	1	
	01	1	
025 / 137	02	2	
	06	6	
	65	X	
	43	RCL	
	00	0	
030 / 142	01	1	
	30	2nd √X	
	54	)	
	56	2nd RTN	
	46	2nd LBL	
035 / 147	17	B'	
	53	(	
	01	1	

LOC	CODE	KEY	COMMENTS
	93	.	
	01	1	
040 / 152	09	9	
	09	9	
	05	5	
	52	EE	
	94	+-	
045 / 157	03	3	
	65	X	
	43	RCL	
	00	0	
	02	2	
050 / 162	54	)	
	56	2nd RTN	
	46	2nd LBL	
	18	C'	
	53	(	
055 / 167	09	9	
	93	.	
	08	8	
	06	6	
	07	7	
060 / 172	52	EE	
	94	+-	
	04	4	
	65	X	
	43	RCL	
065 / 177	00	0	
	01	1	
	54	)	
	56	2nd RTN	
	46	2nd LBL	
070 / 182	19	D'	
	53	(	
	03	3	
	93	.	
	00	0	
075 / 187	05	5	

LOC	CODE	KEY	COMMENTS
	04	4	
	08	8	
	52	EE	
	94	+-	
080 / 192	03	3	
	65	X	
	43	RCL	
	00	0	
	02	2	
085 / 197	54	)	
	56	2nd RTN	
	46	2nd LBL	
	15	E	
	53	(	
090 / 202	43	RCL	
	00	0	
	01	1	
	75	-	
	03	3	
095 / 207	00	0	
	54	)	
	80	2nd ifpos	
	32	SIN	
	53	(	
100 / 212	43	RCL	
	00	0	
	02	2	
	75	-	
	03	3	
105 / 217	02	2	
	54	)	
	80	2nd ifpos	
	33	COS	
	43	RCL	
110 / 222	00	0	
	03	3	

LABELS	
A	V
B	δ_{zt}
C	$N_{R s/t}$
D	
E	ΔTemp
A'	
B'	
C'	
D'	
E'	

REGISTERS	
00	
01	
02	
03	
04	
05	
06	
07	
08	
09	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	

FLAGS	
0	
1	
2	
3	
4	

(Cumulative $N_{Rs/t} \leq 1014$)

TITLE Δ TEMPERATURE RISE TIRE BEAD PAGE 3 OF 7

PROGRAMMER PC Durup DATE 4/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	65	X			03	3			93	.		A
	53	(			02	2			00	0		B
	51	SBR		040 152	54	)			02	2		C
	16	A'			80	2^{nd} lfpos			07	7		D
	85	+			34	tan		080 192	03	3		E
005 117	51	SBR			43	RCL			54	)		A'
	17	B'			00	0			95	=		B'
	54	)		045 157	03	3			81	HLT		C'
	95	=			65	X						D'
	81	HLT			53	(		085 197				E'
010 122	46	2^{nd} LBL			51	SBR						REGISTERS
	33	COS			18	C'						00
	43	RCL		050 162	85	+						01
	00	0			51	SBR						02
	03	3			17	B'		090 202				03
015 127	65	X			85	+						04
	53	(			93	.						05
	51	SBR		055 167	00	0						06
	16	A'			03	3						07
	85	+			02	2		095 207				08
020 132	51	SBR			00	0						09
	19	D'			07	7						10
	75	-		060 172	54	)						11
	93	.			95	=						12
	00	0			81	HLT		100 212				13
025 137	05	5			46	2^{nd} LBL						14
	03	9			34	tan						15
	06	4		065 177	43	RCL						16
	54	)			00	0						17
	95	=			03	3		105 217				18
030 142	81	HLT			65	X						19
	46	2^{nd} LBL			53	(						FLAGS
	32	SIN		070 182	51	SBR						0
	53	(			18	C'						1
	43	RCL			85	+		110 222				2
035 147	00	0			51	SBR						3
	02	2			19	D'						4
	75	-		075 187	75	-						

(Cumulative $N_{R_{s/t}}$ $1014 < N_s \leq 1821$)

TITLE ΔTEMPERATURE RISE TIRE BEAD PAGE 4 OF 7

PROGRAMMER PC Durup DATE 4/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000 112	46	2nd LBL			93	.			05	5	
	11	A			01	1			07	7	
	42	STO		040 152	08	8			06	6	
	00	0			09	9			65	X	
	01	1			52	EE		080 192	43	RCL	
005 117	81	HLT			94	+-			0	0	
	46	2nd LBL			04	4			02	2	
	12	B		045 157	65	X			54	)	
	42	STO			43	RCL			56	2nd RTN	
	00	0			00	0		085 197	46	2nd LBL	
010 122	02	2			02	2			15	E	
	81	HLT			54	)			53	(	
	46	2nd LBL		050 162	56	2nd RTN			43	RCL	
	13	C			46	2nd LBL			00	0	
	42	STO			18	C'		090 202	01	1	
015 127	00	0			53	(			75	-	
	03	3			05	5			03	3	
	81	HLT		055 167	93	.			00	0	
	46	2nd LBL			00	0			54	)	
	16	A'			09	9		095 207	80	2nd ifpos	
020 132	53	(			01	1			32	SIN	
	93	.			03	3			53	(	
	00	0		060 172	52	EE			43	RCL	
	00	0			94	+-			00	0	
	05	5			04	4		100 212	02	2	
025 137	08	8			65	X			75	-	
	01	1			43	RCL			03	3	
	65	X		065 177	00	0			02	2	
	43	RCL			01	1			54	)	
	00	0			54	)		105 217	80	2nd ifpos	
030 142	01	1			56	2nd RTN			33	COS	
	30	2nd $\sqrt{x}$			46	2nd LBL			43	RCL	
	54	)		070 182	19	D'			00	0	
	56	2nd RTN			53	(			03	3	
	46	2nd LBL			93	.		110 222	65	X	
035 147	17	B'			00	0			53	(	
	53	(			00	0					
	06	6		075 187	01	1					

LABELS	
A	V
B	δzt
C	$N_{R_{s/t}}$
D	
E	ΔTemp
A'	
B'	
C'	
D'	
E'	

REGISTERS	
00	
01	
02	
03	
04	
05	
06	
07	
08	
09	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	

FLAGS	
0	
1	
2	
3	
4	

(Cumulative $N_{Rs/t}$ 1014 : 1821)

TITLE ΔTEMPERATURE RISE TIRE BEAD PAGE 5 OF 7

PROGRAMMER PC Durup DATE 4/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	51	SBR			02	2			00	0		A
	11	A'			54	)			01	1		B
	85	+		040 152	80	2nd ifpos			04	4		C
	51	SBR			34	tan			00	0		D
	17	B'			43	RCL		080 192	09	9		E
005 117	54	)			00	0			54	)		A
	95	=			03	3			95	=		B
	81	HLT		045 157	65	X			81	HLT		C'
	46	2nd LBL			53	(						D
	33	COS			51	SBR		085 197				E
010 122	43	RCL			18	C'						REGISTERS
	00	0			85	+						00
	03	3		050 162	51	SBR						01
	65	X			17	B'						02
	53	(			85	+		090 202				03
015 127	51	SBR			93	.						04
	16	A'			00	0						05
	85	+		055 167	01	1						06
	51	SBR			06	6						07
	19	D'			05	5		095 207				08
020 132	75	-			05	5						09
	93	.			54	)						10
	00	0		060 172	95	=						11
	03	3			81	HLT						12
	00	0			46	2nd LBL		100 212				13
025 137	06	6			34	tan						14
	04	4			43	RCL						15
	54	)		065 177	00	0						16
	95	=			03	3						17
	81	HLT			65	X		105 217				18
030 142	46	2nd LBL			54	(						19
	32	SIN			51	SBR						FLAGS
	53	(		070 182	18	C'						0
	43	RCL			85	+						1
	00	0			51	SBR		110 222				2
035 147	02	2			19	D'						3
	75	-			75	-						4
	03	3		075 187	93	.						

(Cumulative $N_{R_{s/t}}$ >1821)

TITLE Δ TEMPERATURE RISE TIRE BEAD PAGE 6 OF 7

PROGRAMMER PC Durup DATE 4/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	46	2nd LBL			02	2			02	2		A V
	11	A			93	.			03	3		B δ_{zt}
	42	STO		040 152	08	8			04	4		C $N_{Rs/t}$
	00	0			04	4			04	4		D
	01	1			00	0		080 192	52	EE		E ΔTEMP
005 117	81	HLT			05	5			94	+-		A'
	46	2nd LBL			52	EE			04	4		B'
	12	B		045 157	94	+-			65	X		C'
	42	STO			04	4			43	RCL		D'
	00	0			65	X		085 197	00	0		E'
010 122	02	2			43	RCL			02	2		REGISTERS
	81	HLT			00	0			54	)		00
	46	2nd LBL		050 162	02	2			56	2nd RTN		01
	13	C			54	)			46	2nd LBL		02
	42	STO			56	2nd RTN		090 202	15	E		03
015 127	00	0			46	2nd LBL			53	(		04
	03	3			18	C'			43	RCL		05
	81	HLT		055 167	53	(			00	0		06
	46	2nd LBL			01	1			01	1		07
	16	A'			93	.		095 207	75	-		08
020 132	53	(			06	6			03	3		09
	93	.			05	5			00	0		10
	00	0		060 172	06	6			54	)		11
	00	0			02	2			80	2nd ifpos		12
	02	2			52	EE		100 212	32	SIN		13
025 137	06	6			94	+-			53	(		14
	06	6			04	4			43	RCL		15
	07	7		065 177	65	X			00	0		16
	65	X			43	RCL			02	2		17
	43	RCL			00	0		105 217	75	-		18
030 142	00	0			01	1			03	3		19
	01	1			54	)			02	2		FLAGS
	30	2nd $\sqrt{X}$		070 182	56	2nd RTN			54	)		0
	54	)			46	2nd LBL			80	2nd ifpos		1
	56	2nd RTN			19	D'		110 222	33	COS		2
035 147	46	2nd LBL			53	(			43	RCL		3
	17	B'			07	7						4
	53	(		075 187	93	.						

(Cumulative $N_{R_{s/t}}$ >1821)

TITLE ΔTEMPERATURE RISE TIRE BEAD PAGE 7 OF 7

PROGRAMMER PC Durup DATE 4/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LABELS
000 112	00	0			00	0			85	+		A
	03	3			02	2			51	SBR		B
	65	X		040 152	75	-			19	D'		C
	53	(			03	3			75	-		D
	51	SBR			02	2		080 192	93	.		E
005 117	16	A'			54	)			00	0		A'
	85	+			80	2^{nd} ifpos			00	0		B'
	51	SBR		045 157	34	tan			04	4		C'
	17	B'			43	RCL			04	4		D'
	54	)			00	0		085 197	02	2		E'
010 122	95	=			03	3			01	1		REGISTERS
	81	HLT			65	X			54	)		00
	46	2^{nd} LBL		050 162	53	(			95	=		01
	33	COS			51	SBR			81	HLT		02
	43	RCL			18	C'		090 202				03
015 127	00	0			85	+						04
	03	3			51	SBR						05
	65	X		055 167	17	B'						06
	53	(			85	+						07
	51	SBR			93	.		095 207				08
020 132	16	A'			00	0						09
	85	+			00	0						10
	51	SBR		060 172	09	9						11
	19	D'			06	6						12
	75	-			03	3		100 212				13
025 137	93	.			09	9						14
	00	0			54	)						15
	01	1		065 177	95	=						16
	04	4			81	HLT						17
	02	2			46	2^{nd} LBL		105 217				18
030 142	00	0			34	tan						19
	54	)			43	RCL						FLAGS
	95	=		070 182	00	0						0
	81	HLT			03	3						1
	46	2^{nd} LBL			65	X		110 222				2
035 147	32	SIN			53	(						3
	53	(			51	SBR						4
	43	RCL		075 187	18	C'						

DISTANCE TRAVELED

(Pages A-14 and A-15)

SAMPLE PROBLEM

- Distance Traveled in a Turn

Input	Key
R_B = 150 Feet	A
δ_{TZ} = 29.7 Percent	B
ℓ_n = 26 Inches	2nd A'
d_o = 49.5 Inches	2nd B'
δ_{100} = 12.875 Inches	2nd C'
Answer	
N_{R_T} = 18.89 Revolutions	D

- Distance traveled straight taxi

Input	Key
δ_{TZ} = 25.0 Percent	B
D_s = 3000 Feet	C
d_o = 49.5 Inches	2nd B'
δ_{100} = 12.875 Inches	2nd C'
Answer	
N_{R_S} = 241.99 Revolutions	E

SR-52 User Instructions

TITLE DISTANCES TRAVELED PAGE 1 OF 2

		◄A◄		
R_B	δ_{TZ}	D_s	N_{RB}	N_s
ℓ_n	d_o	δ_{100}		

		◄B◄		

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter Program A		CLR	2nd	read	
	Distance Traveled in a Turn					
2	Enter Turn Radius, R_B		A			
3	Enter Tire Deflection, δ_{TZ}		B			
4	Enter one Half Bogie Tread, ℓ_n		2nd	A'		
5	Enter Tire Diameter, d_o		2nd	B'		
6	Enter Deflec. at 100%, δ_{100}		2nd	C'		
7	Calculate Revolution, N_{RT}		D			
	Distance Traveled Straight Taxi					
1	Enter Tire Deflection, δ_{TZ}		B			
2	Enter Distance Traveled, D_s		C			
3	Enter Tire Diameter, d_o		2nd	B'		
4	Enter Deflec. at 100%, δ_{100}		2nd	C'		
5	Calculate Revolutions, N_{RS}		E			

 Part No. 1220479

TITLE DISTANCES TRAVELED PAGE 2 OF 2

PROGRAMMER PC Durup DATE 8/10/78

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000 112	46	2nd LBL			07	7			08	8	
	11	A			05	5			00	0	
	42	STO		040 152	65	X			00	0	
	00	0			53	(			65	X	
	01	1			01	1		080 192	43	RCL	
005 117	81	HLT			02	2			00	0	
	46	2nd LBL			65	X			05	5	
	12	B		045 157	43	RCL			55	÷	
	42	STO			00	0			59	2nd π	
	00	0			01	1		085 197	55	÷	
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LABELS	
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REGISTERS	
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04	δ_{TZ}
05	D_s
06	δ_{100}
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